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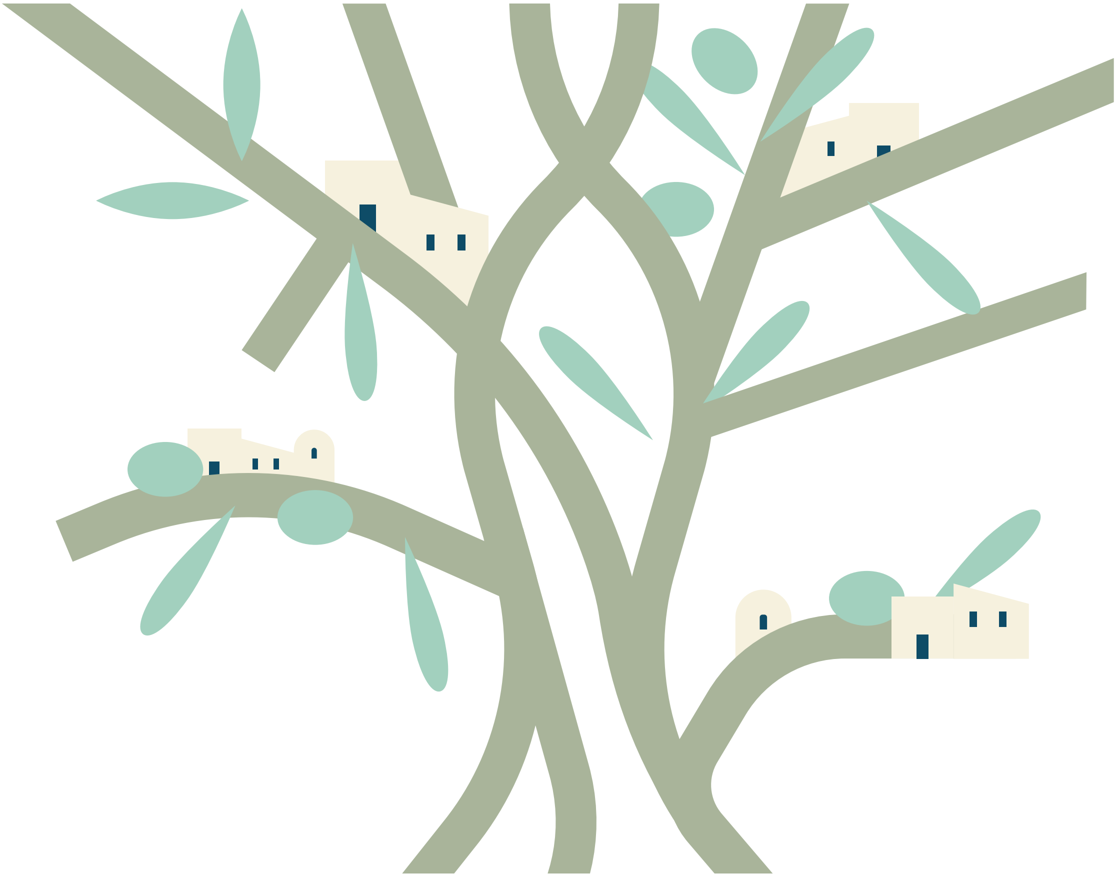

Fintech Gender Disparities in Africa
MOUHEB KHCHOUM,
WAJDI BARDI

The effects of non-extension of the Black Sea Grain Deal on Global Market
AHMED AL MAHRUQUI,
CHOKRI THABET,
MOHAMED ABDELBASSET CHEMINGUI

Rethinking Sustainability in the EU Agri-Food Sector
ELENI ZAFEIRIOU,
SPYRIDON GALATSIDAS,
GEORGIOS TSANTOPOULOS,
SPYRIDON SOFIOS,
EVANGELIA SIAKOU,
GARYFALLOS ARABATZIS

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Contents

Foreword pag. 1

Mouheb Khchoum, Wajdi Bardi
Fintech gender disparities in Africa pag. 3

Ahmed Al Mahruqui, Chokri Thabet, Mohamed Abdelbasset Chemingui
To what extent the non-extension of the Black Sea grain deal is disrupting global and Arab wheat markets pag. 21

Eleni Zafeiriou, Spyridon Galatsidas, Georgios Tsantopoulos, Spyridon Sofios, Evangelia Siakou, Garyfallos Arabatzis
Assessing environmental and economic dynamics in the EU agri-food sector: The impact of imports through a BVAR analysis pag. 37

Arturo García-Agulló Meliveo, Adoración Mozas-Moral, Sebastián Sánchez-Villasclaras
Distribution strategies in the value chain of Spanish virgin olive oils pag. 59

Nahla Hwalla, Ramia Al Bakain, Antonio Trani, Donato Mondelli, Biagio Di Terlizzi, Mouïn Hamzé
Exploring the nutritional and nutraceutical significance of legumes: A comparative analysis across Mashreq countries pag. 73

Abir Gharbi, Mariem Arfaoui, Sonia Boudiche, Mehrez Ameur
Dietary patterns and socioeconomic factors affecting Mediterranean diet adherence in Tunisia pag. 89

Theodoros Markopoulos, Dimitrios N. Kaziolas, Christos Staboulis
Tracing the root of the evil in the carbon footprint of tomato production: Implications for optimization process and policy formulation pag. 109

Roberto Henke, Emanuela Burgio, Cristina Vaquero-Piñeiro
Water management for agriculture in a Mediterranean area: The case of processing tomatoes in Italy pag. 123

Rahmiye Figen Ceylan, Ramu Govindasamy, Burhan Ozkan
Food price dynamics in Turkey's agricultural export market with selected machine learning approaches pag. 145

Notes
Abderraouf Laajimi
The international olive sector: challenges in the face of climate change pag. 157

Foreword

Khchoum and Bardi investigate the drivers of fintech gender disparities in Africa. They find significant gender disparities in fintech usage; 38% of men use fintech, compared to only 29% of women. The authors demonstrate that socioeconomic and cultural factors are the main drivers of gender disparities in Africa, as women in the continent face greater inequality in the workplace, in education, literacy, and the law, whichmakes it more difficult for them to access digital finance.

The effects of conflict between Russia and Ukraine on the global wheat market, particularly impacting Arab countries that heavily rely on wheat imports analysed by *Al Mahruqui, Thabet and Abdelbasset Chemingui*. The main effect is the volatility that threatens food security and fiscal stability in Arab nations, especially those with limited or no wheat subsidies. The authors suggest that the nonrenewal of the Black Sea agreement could raise global wheat prices by 3-4% on average, though the overall impact is expected to be short-lived due to the market's resilience. The authors emphasize the need for proactive import planning and the importance of agricultural policies and trade finance in shaping wheat market dynamics.

Zafeiriou et al. investigate the environmental impact of the EU agri-food sector, focusing on emissions per capita and their relationship with economic growth. The authors show that greening efforts in the sector have not been matched by sufficient economic growth. Despite progress in sustainable practices, economic expansion has fallen short of offsetting environmental costs, with imports playing a critical role. The study calls for future research to develop a comprehensive index incorporating diverse variables to better assess sustainability efforts in the agri-food sector.

García-Agulló Meliveo et al. analyze the value chain of virgin olive oils in Spain, establishing the relationship between then prices of virgin olive oils at origin and the retail prices paid by the end consumer. The authors highlight that the retail price of virgin olive oils by the retailers does not reflect the real production cost of the product, since they obey more to a concept of customer attraction strategy on the part of the distribution.

Hamzé et al. investigate the nutritional and nutraceutical profiles of four legume species – bean, faba bean, chickpea, and lentil – collected from Lebanon, Syria, Jordan, Palestine, and Egypt. Chemical analyses assessed antioxidant, nutritional and nutraceutical properties among legume varieties and regions. The results highlight the role of genetic, environmental, and geographical factors in legume quality, emphasizing their potential in addressing malnutrition and promoting sustainable food systems.

Gharbi, Arfaoui, Boudiche and Ameur assess Tunisian consumers' adherence to the Mediterranean diet (MD) and identify socioeconomic factors influencing this adherence. The results of the Mediterranean Diet Adherence Screener (MEDAS) score calculation allowed the classification of consumers into three groups: moderate adherence group (65.5% of the total population), high adherence (5.8%) and low adherence group (28.7%). The results highlight the need for targeted promotion and marketing strategies to raise awareness of the Mediterranean diet's benefits and the health risks associated with modern diets.

A comprehensive evaluation of the carbon footprint in tomato production in Greece by means of a Life Cycle Assessment is provided by *Markopoulos, Kaziolas and Staboulis*. Results indicate that the energy required to produce the tomato is the factor that has the greatest environmental impact. Tomatoes are an essential component of global food systems. Thus, even marginal improvements in the carbon efficiency of tomato production could yield significant environmental benefits, and a detailed carbon footprint analysis could influence policy and practice.

Henke et al. examine the effects of different irrigation methods and water supply services on the economic performance of farmers in the processing tomato sector. The analysis reveals economic benefits generated by adopting a self-supply water management strategy and more sustainable irrigation techniques (micro-irrigation), especially in regions experiencing acute droughts and higher temperatures. Findings emphasize the importance of considering the region specific context when implementing policy interventions, technological innovations, and governance structures.

Figen Ceylan et al. analyze a specific food price index related to Turkish food exports, with the goal of evaluating the factors contributing to volatility in this index. The results revealed that rising prices of exportable products are driven by various factors, including cost items, food price inflation, unemployment levels (as an indicator of income), and exchange rates. The predictions suggest that variations in aggregate price levels, exchange rates, and technology-related and import-dependent costs are critical for observation and evaluation. These factors appear to play a more significant role in determining price inflation for Turkish agricultural and food products.

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Fintech gender disparities in Africa

MOUHEB KHCHOUM*, WAJDI BARDI**

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Abstract

This paper investigates the drivers of fintech gender disparities in Africa. We use a novel fintech dataset for 35 economies in Africa over three different years 2014-2017 and 2021. Using the Generalized Linear Model (GLM) and Panel Least Squares methods. It finds significant gender disparities in fintech usage; 38% of men use fintech, compared to only 29% of women. It also demonstrates that socioeconomic and cultural factors are the main drivers of gender disparities in Africa, as women in the continent face greater inequality in the workplace, in education, literacy, and the law, which makes it more difficult for them to access digital finance. In addition, we find that women use fintech more frequently, financial services are easier to get, and financial inclusion is encouraged when women are empowered politically, included in democratic decision-making processes, and gender equality is advanced globally.

Keywords: *Fintech, Gender disparities, Africa region, Gender inequality, Financial inclusion.*

1. Introduction

The financial system in Africa is limited in scope and lacks development. In Africa, low- and unstable-income levels, inflationary environments, high rates of illiteracy, inadequate infrastructure, governance issues, and the high cost of banking are some of the factors cited to explain the underdeveloped financial sector and its limited outreach (Triki and Faye, 2013). In Africa, adults who live in rural areas usually mention the distance to a bank as a deterrent to opening an account, while younger adults typically cite inadequate documentation. The idea that easily available financial services may contribute to the fight against poverty and promote economic growth is gaining traction. The belief that the poor can be lifted out of the cycle of poverty through access to and usage of quality financial services is the driving force behind the widespread adoption of policies, programs, and reform measures that aim to promote financial inclusion. The continent has experienced a notable upsurge in financial technology innovation in the last ten years, which has transformed the accessibility and utilization of financial services. An expanding middle class, the need to close the financial inclusion gap, and the increasing adoption of smartphones have all contributed to this issue. Across the continent, fintech businesses have proliferated, providing a wide range of services, including digital payment systems, insurtech, peer-to-peer lending, and mobile

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banking. Financial inclusion has been primarily fueled by the use of digital financial services (GSMA, 2020; Pazarbasioglu *et al.*, 2020; World Bank, 2020a, 2020b). Recent technological developments and the adoption of digital financial services, such as mobile money, internet banking, and electronic payment systems, have not only increased the efficiency of service delivery but also decreased the cost of financial transactions, increasing financial inclusion for the poor (Sahay *et al.*, 2020; World Bank, 2020a). Alsan *et al.* (2017) found a direct link between gender inequality in financial inclusion and overall inequality.

African women face significant challenges in accessing financial services, which hampers their economic participation. Traditional gender roles and social norms further restrict their economic activities and decision-making power. According to the International Monetary Fund (IMF), women's limited access to financial services in Africa significantly impacts social and economic progress, particularly in sectors like agriculture where women are predominant. Furthermore, there are no equal opportunities for women because they are underrepresented in leadership positions, higher-paying professions, and even education which widens socioeconomic inequality. Kerras *et al.* (2022) emphasize that women's access to technology and education plays a crucial role in promoting sustainability in the agri-food sector. In the same vein, Parrilla González and Ortega Alonso (2022) point out that gender perspectives, heritage, and innovation are critical for achieving sustainability goals in the olive oil cooperative sector, a model that could inspire gender-inclusive fintech strategies in Africa.

The usage of financial products and services is a topic covered in a higher proportion of digital financial inclusion literature than in financial inclusion literature. Inequality affects efforts to reduce poverty in low- and middle-income countries. Because of discriminatory social norms that deprive women of their rights and educational opportunities, there is a gender gap in technology use, financial illiteracy, digital illiteracy, and ultimately financial exclusion and digital financial exclusion (Ojo, 2022). The impact of the gender gap on financial inclusion is confirmed by Delechat *et al.* (2018). The unbanked population is proof that low- and middle-income countries have a high degree of financial exclusion (Naumenkova *et al.*, 2019).

Moreover, absence of financial literacy initiatives to facilitate loan availability could lead to impoverished people accruing excessive debt, thereby exacerbating their poverty. In every area of the economy, including manufacturing, distribution, education, banking, and health, digital technology has changed everything. These include time limits, lack of digital expertise, access, which makes internet connectivity difficult, and the usage of Digital Financial Services (DFS) (Mariscal *et al.*, 2018). Obstacles to DFS for women include societal beliefs, trust, confidence, a lack of digital devices like laptops and smartphones, the high cost of internet data, laws that discriminate against women, gaps in digital knowledge and skills, and a lack of technical skills and competencies (Molinier, 2019; Krieger-Boden and Sorgner, 2018), but previous research and data is not sufficient and the issue needs further investigation. Additionally, low earnings, low incomes, low literacy rates, sociocultural factors, digital exclusion and education, issues about pricing and accessibility, fears about safety and security, and discouragement from loved ones Knowledge and information asymmetry is one of the barriers to DFS for women (Chetty *et al.*, 2018). Despite their focus on DFS, the researchers contend that the use and spread of Information Communication Technologies (ICT) has a positive relationship with the decrease of poverty and inequality.

The purpose of this paper is to determine the factors that contribute to gender differences in fintech in Africa. We examined the relationship between gender inequality and fintech, examining the gender disparities from the perspective of using digital financial services. We also looked at the elements related to law, culture, social norms, and uneven access to the employment, education, and literacy. In addition, we offer several suggestions that help address the gender gap in digital financial inclusion. In addition to improving access to financial services and reducing economic and financial exclusion, digital financial inclusion may help women gain more power and see the UN Sustainable Development Goals (SDG) in developing countries fulfilled by 2030.

The rest of this paper is organized as follows. Section 2 presents a review of the literature. Section 3 describes our empirical analysis. In section 4, we present our findings and discuss them in line with the relevant literature and findings, and we develop analysis of robustness checks. Our conclusions will be outlined in section 5.

2. Literature review

Women are still more likely to be unbanked or unbanked globally than men. They manage their household finances less frequently than males do (Guiso and Zaccaria, 2021) and are less likely to own a bank account (Demirgc-Kunt *et al*., 2017). There is rising optimism that new financial technologies, or "fintechs," can increase financial inclusion and eliminate the gender gap in access to financial services. Traditional financial institutions and more recent fintech companies are both using new technologies and non-traditional data to make investments that are more cost-effective and cater to consumer requirements (Thakor, 2020; Philippon, 2019; Boot *et al*., 2021 and Arner *et al*., 2020). Fintech may be used to assist close the gender disparities in access to and use of financial services; however, there is insufficient evidence to support this claim.

By expanding access to financial services and eliminating financial and economic exclusion, digital financial inclusion could help in the empowerment of women and the achievement of the United Nations 2030 Sustainable Development Goals (SDG) in developing nations. Over the past ten years, there has been a noticeable increase in the use of technology and the acceptance of digital financial services (DFS), such as conducting financial transactions online and using mobile devices. This trend was further exacerbated during the COVID-19 pandemic. Since it allows those, who would not have otherwise been able to access traditional financial services to conduct financial transactions from home, and businesses fintech has proven very useful in achieving the objectives of financial inclusion. Nonetheless, disparities in financial inclusion across genders still exist. Women have accounted for 65% of the world's population, compared to 72% of men (Demirgüç-Kunt *et al*., 2018). As financial technologies become more accessible and easier to use, they can help women overcome some of these barriers and become financially empowered (Sioson and Kim, 2019).

Although there are still significant differences between regions and nations, financial inclusion indexes created by Sahay *et al*. (2020) indicate that DFSs have in fact assisted in closing gender gaps in a number of nations. Investigating the reasons behind these discrepancies is crucial for bridging the gender disparities in fintech since increased digital financial inclusion is linked to economic growth, which is good for society overall (Khera *et al*., 2021). Furthermore, barriers to DFS for women include a lack of digital equipment such as laptops and mobile phones, high internet data costs, discriminatory legislation, digital knowledge, and skill gaps, as well as social beliefs, trust, confidence, and inadequate technical skills and competences (Krieger-Boden and Sorgner, 2018). Disadvantageous social norms that deny women's rights and educational opportunities are also to blame for the gender disparity in technology use, financial illiteracy, digital illiteracy, and, ultimately, financial and digital financial exclusion.

According to Ahmed and Gillwald (2021), and Antonio and Tuffley (2014), the digital divide is rooted in historically established and persistent gender inequities related to barriers to internet access and technology use. The digital divide is associated with a skills gap and a lack of access to ICT. Fintech can play a pivotal role in alleviating income inequality. It can generate opportunities for the poor through job creation.

It can also lead to improved government services and tax collection while reducing corruption. Asongu et al (2017) investigated the interplay between ICT (i.e. mobile, internet, and broadband penetration) and inclusive growth in Sub-Saharan Africa over the period 2000–2012. They found a positive relationship between ICTs and inclusive growth. Asongu (2015) found an inverse relationship between income inequality and mobile penetration in Africa. Likewise, Asongu and Odhiambo (2019) identified an inverse relationship between mobile, internet, and broadband penetration and inequality using a panel of 48 African countries. Most studies have found that FinTech and ICT are key drivers of financial inclusion (Kulkarni and Ghosh, 2021; Tchamyou *et al*., 2019). However, the fintech-financial inclusion nexus might differ depending on the financial inclusion dimensions, in addition to the type of financial service (payments, savings, credit, and insurance). Chea *et al*. (2021) looked into the extent of the gender disparity in the Association of Southeast Asian Nations (ASEAN) payments ecosystem in light of this. They found that women are more likely than males to employ conventional cash payment methods. In contrast, they discovered evidence of gender differences in the more advanced mobile money payment channels. These results, which are believed to withstand many sensitivity tests, also show that in more developed ASEAN countries like Singapore and Malaysia, there is a significant gender difference in the usage of mobile money. To assess data on the recent use of different payment channels and ascertain if the post-pandemic divide in ASEAN has widened or contracted, more study is desperately needed.

According to Ahmed and Gillwald (2021), gender differences that have historically been associated with barriers to internet access and technology use are at the root of the digital divide. The lack of access to ICT and the skills disparities are related to the digital divide. In Zambia Mwenge and Bwalya (2020) found that Women are typically more risk cautious and have lower risk tolerance levels. Low earnings also limit women because they are typically employed in low-paying jobs including domestic work, farming, and self-employment. Gammage *et al*. (2017) determine that digital finance is essential for enhancing the resilience, earnings, and standard of living of marginalized populations including women and young people. By lowering the costs of providing and gaining access to financial services, enhancing security, and lowering the risks involved in accessing financial services, DFSs play a crucial role in promoting financial inclusion. Fintech makes financial transactions faster and guarantees that low-income individuals receive specialized services that are tailored to their needs. Were *et al.* (2021) has provided research of Tanzania's gender differences in financial inclusion utilizing metrics including usage and access to digital and traditional bank-based financial services, especially mobile money services. Several socioeconomic factors, such as low income, restricted access to digital financial tools like smartphones, and low financial literacy, all contribute to the gender gap in financial inclusion by preventing women from effectively accessing and using formal financial services.

The data demonstrates that the gender gap in digital financial inclusion is not influenced by the state's level of economic growth. Important obstacles preventing women from using digital financial services are also identified in the study. Although most studies focused on the fintech gender gap, not on gender disparities, few researchers have analyzed gender disparities, especially in Africa. Our study contributes to the literature by utilizing recent databases to analyze the drivers of gender disparities in Africa, using socio-economic and cultural indicators.

3. Empirical Analysis

3.1. *Methodology and data*

To carry out this empirical study we used a database of the Global Findex Database over three times of periods 2014, 2017, and 2021. This data launched by the World Bank in 2011, provides comparable indicators showing how people around the world save, borrow, make payments, and manage risk. The 2014 edition of the database reveals that 62 percent of adults worldwide have an account at a bank or another type of financial institution or with a mobile money provider. Between 2011 and 2014, 700 million adults became account holders while the number of those without an account the unbanked dropped by 20 percent to 2 billion. A growth in account penetration of 13 percentage points in developing economies and innovations in technology particularly mobile money, which is helping to rapidly expand access to financial services in Sub-Saharan Africa. Along with these gains, the data also show that big opportunities remain to increase financial inclusion, especially among women and poor people. The indicators in the 2017 Global Findex database are drawn from survey data covering almost 150,000 people in 144 representing more than 97 percent of the world's population. The 2021 edition, based on nationally representative surveys of about 128,000 adults in 123 economies. We did not use the database of 2011 because of the lack of data when we compared it by 2014, 2017, and 2021.

3.2. *Model specifications*

To understand and analyze the drivers of gender diversities in fintech in Africa. We use two methods of estimation: the method of Generalized Least Squares (GLS) and the method of Least-Squares Estimation of panel models.

We regress the gender diversities in digital financials on socio-economic and cultural factors, and measures of gender disparities in fintech across three times – 2014, 2017, and 2021. The sample of study composed of 35 economies in Africa (See Appendix 1). The model is largely inspired by Khera *et al*. (2022).

We estimate the following model:

$$FinDPF_{it} = \alpha_1 + \alpha_2 EDU_{it} + \alpha_3 WBL_{it} + \quad (1)$$
$$+ \alpha_4 GDP_{it} + \alpha_5 PEM_{it} + \alpha_6 LFP_{it} + \alpha_7 LIT_{it} + \varepsilon_{it}$$

We used a panel data analysis in which the index t refers to the observation years and i refers to a group of African countries.

Where: $FinDPF$: represents the percentage of females who made or received a digital payment (% age 15+). EDU: Educational attainment of female over male value in country i in year t. LIT: Female literacy rate over male value in country i in year t. PEM: Process of transferring various elements of power (resources, capabilities, and positions). Political empowerment requires inclusion in democratic decision-making processing country i in year t. LFP: is the ratio of female to male labor force participation rate in country i in year t. WBL: is the Women, Business, and Law index for country i for year t measures cultural factors that might affect gender disparities and GDP is the Real GDP *per capita*.

According to Table 2, the mean value we find

Table 1 - Variables definitions.

Variables	*Measurements/Definitions*	*Sources*
DPF	Made or received a digital payment, female (% age 15+).	Global Findex Database World Bank Asongu and Nwachukwu, 2018; Asongu and Odhiambo, 2019
WBL it	Women, Business and Law index for country I for year t	World Bank 2014, 2017 and 2021
Educational attainment	Educational attainment of female over male value	The Global Gender Gap Report 2014, 2017 and 2021; World Economic Forum Bank
Political Empowerment	Process of transferring various elements of power (resources, capabilities, and positions). Political empowerment requires inclusion in democratic decision-making process	The Global Gender Gap Report 2014, 2017 and 2021; World Economic Forum Bank
Ratio of female to male labor force participation rate (%) (modeled ILO estimate)	Ratio of female to male labor force participation rate in country *i*-year *t*. Dividing female labor force participation rate by male labor force participation rate and multiplying by 100	World BANK: https://data.worldbank.org/indicator/SL.TLF.CACT.FM.ZS
Literacy	Female literacy rate over male value	The Global Gender Gap Report 2014, 2017 and 2021; World Economic Forum Bank
Control variable		
Economic development	GDP per capita	WDI (2022)

Table 2 - Descriptive statistics.

	DPF	*DPM*	*LIT*	*EDU*	*WBL*	*GDP*	*PEM*	*LAB*
Mean	0.2914	0.3829	1.0554	0.8208	67.7607	96.6231	0.22070	61.6831
Median	0.26	0.4	0.751	0.85	71.875	6	0.2	67
Maximum	0.75	0.84	13	1	88.125	968	0.66	95.1869
Minimum	0.04	0.04	0.3	0.3	38.75	1.19	0.0089	22.3227
Std. Dev.	0.1771	0.1815	1.8973	0.1489	13.3122	248.4562	0.1353	21.6226
Skewness	0.7182	0.1529	5.6474	-1.41012	-0.3500	2.6193	0.9950	-0.42828
Kurtosis	2.8339	2.7094	33.323	5.1879	1.9165	8.0614	3.9080	1.9365
Jarque-Bera	9.1480	0.7787	4580.9	55.7423	7.2797	232.1506	20.9327	8.15730
Probability	0.0103	0.6774		0.0000	0.0262	0.0000	0.0000	0.01693
Sum	30.599	40.207	110.82	86.194	7114.875	10145.428	23.174	6476.731
Sum Sq.	3.2636		374.40	2.3065	18430.534	6419974.29	1.9061	48624.15
Observations	105	105	105	105	105	105	105	105

large fintech gender disparities in Africa; while 38% of men use fintech products, only 29% of women do. Descriptive statistics further shed light on the relationship between the dependent variable, representing digital payments made or received by females (DPF), and the independent variables (LIT, EDU, WBL, PEM, and LAB). On average, a one-unit increase in the corresponding independent variable (LIT, EDU, WBL, PEM, LAB) is associated with a 0.26-unit increase dependent variable.

Examining the distribution of the dependent variable (DPF), we observe a maximum value of 0.75. This signifies that the highest recorded value for this variable in our dataset is 0.75. Identifying such extreme values is crucial for detecting outliers and understanding the variability within our dataset. Conversely, the minimum value for DPF is 0.04, indicating that the lowest observed values for digital payments made or received by females are 0.04. These minimum values offer insights into the lower bounds of the data distribution. Our analysis also includes an assessment of the standard deviation, which is relatively small at 0.177. This small standard deviation suggests that the values of the variables are closely clustered around their respective means.

Analysis of correlation is presented in Table 3. The dependent variable, which stands for digital payments made or received by women (DPF), has a negative correlation (-0.129) with GDP and a substantial positive correlation (0.268) with WBL (0.293).EDU has a negative correlation (-0.447) with LIT and a positive correlation (0.268, 0.415, and 0.287) with DPF, WBL, and LAB.

WBL shows a negative correlation (-0.214) with LIT and positive correlations (0.415, 0.019) with EDU and LAB.GDP has a minor

Table 3 - Correlation Matrix.

	DPF	*EDU*	*WBL*	*GDP*	*PEM*	*LAB*	*LIT*
DPF	1	0.2680	0.2938	-0.1299	0.2598	-0.0316	-0.0563
EDU	0.2680	1	0.4146	-0.0144	0.1603	0.2871	-0.4467
WBL	0.2938	0.4146	1	0.1010	0.1068	0.0186	-0.2136
GDP	-0.1299	-0.0144	0.1010	1	0.0328	-0.0757	-0.0356
PEM	0.2598	0.1603	0.1068	0.0328	1	-0.0256	-0.1360
LAB	-0.0316	0.2871	0.0186	-0.0757	-0.0256	1	0.1927
LIT	-0.0563	-0.4467	-0.2136	-0.0356	-0.1360	0.1927	1

positive association with WBL (0.101) and a negative correlation with DPF (-0.130). PEM and DPF (0.260), EDU (0.160), and WBL (0.107) have favorable associations. LAB exhibits a negative correlation (-0.032) with DPF and a positive correlation (0.287) with WBL and 0.019. The correlations between LIT and WBL (-0.214), PEM (-0.136), and EDU (-0.447) are all negative. The magnitude and direction of the linear relationships between the variables are shown by these values.

These correlations provide insights into the relationships between variables. The correlations between predictor variables are very small (close to zero) or moderate; it suggests that the variables are likely independent of each other, reducing concerns about multicollinearity.

3.3. *Specification tests*

The Breusch-Pagan Test is used to determine whether or not heteroscedasticity is present in a regression model (Table 4). The test uses the following null and alternative hypotheses:

- Null Hypothesis (H0): Homoscedasticity is present (the residuals are distributed with equal variance);
- Alternative Hypothesis (HA): Heteroscedasticity is present (the residuals are not distributed with equal variance).

The p-value of (0.0000) suggests that there is evidence to reject the null hypothesis of homoscedasticity (constant variance of errors). So, there might be heteroscedasticity in our model. Heteroscedasticity refers to the situation where the variance of the errors is not constant across all levels of the independent variables. The Pesaran Scaled LM Test is associated with panel data and is used to test for cross-sectional dependence. The low probability value (0.0000) suggests evidence against the null hypothesis of no cross-sectional dependence. So, it proves that there is cross-sectional dependence in our data.

The output provided from a Likelihood Ratio (LR) Test concerns heteroskedasticity in the context of a regression model (Table 5). The null hypothesis being tested is that the residuals are homoskedastic (constant variance) against the alternative hypothesis that the residuals exhibit (heteroskedasticity-varying variance). Here is a breakdown of the key elements in the output.

The p-value is associated with the Likelihood Ratio Test. In this case, it is very small (0.0001), suggesting strong evidence against the null hypothesis. The LR test strongly rejects the null hypothesis of homoskedastic residuals, suggesting the presence of heteroskedasticity. The

Table 4 - The Breusch-Pagan and Persaran Test.

Test	*Statistic*	*d.f.*	*Prob.*
Breusch-Pagan LM	922.4877	595	0.0000*
Pesaran scaled LM	9.493394		0.0000*

**Indicate significance at 1 % significance.*

Table 5 - Likelihood Ratio (LR) Test for Heteroskedasticity.

	Value	*df*	*Probability*
Likelihood ratio	75.85191	35	0.0001
LR test summary:	Value	df	
Restricted LogL	44.47944	99	
Unrestricted LogL	82.40539	99	

Variable	*Coefficient*	*Std. Error*	*t-Statistic*	*Prob.*
LAB	-0.001645	0.000541	-3.042630	0.0030
EDU	0.049579	0.053272	0.930669	0.3543
PEM	0.183305	0.057804	3.171173	0.0020
LIT	0.008249	0.007881	1.046780	0.2978
WBL	0.004397	0.000404	10.88713	0.0000
GDP	-0.000100	2.89E-05	-3.453506	0.0008

coefficients and associated statistics provide information about the relationship between the dependent variable (DPF) and the independent variables (LAB, EDU, PEM, LIT, WBL, GDP). The weighted statistics are also provided, indicating the performance of the model with cross-section weights applied.

4. Results and discussions

4.1. *Results*

Tables 6 and 7, show the results of the random effects panel Linear Regression Model with two methods generalized least squares (GLS) and Least-squares estimation of panel models. The application descriptive statistics of the data used in this study for the period 2014, 2017, and 2021. Digital Payment made by Females as measured by the percentage of females who made or received digital payment.

The first objective of our study was to investigate what are the drivers of gender disparities in Fintech in African countries by exploring socioeconomic and cultural factors. Excluding the index of economic development GDP per capita, all other variables show a substantial positive impact on the dependent variable. The findings reveal a significant positive relation between the dependent variable which represents the percentage of females who made or received a digital payment (% age 15+) and independent variables (Education, literacy rate, women's political empowerment, and the Women, Business and Law index), we find that all coefficients have statistical significance. This indicates that the independent variables in our model significantly influence the dependent variable, DPF.

4.2. *Discussion of Findings*

Using a novel fintech dataset for 35 economies in Africa over three distinct years 2014-2017 and 2021, we find large fintech gender disparities in Africa; while 38% of men use fintech, only 29% of women do, we determine that the drivers of gender disparities in Africa consist of socio-economic and cultural factors because

Table 6 - Results of estimation.

Dependent Variable: DPF Method 1: Generalized Linear Model (Newton-Raphson / Marquardt steps)												
	Model 1			*Model 2*			*Model 3*			*Model 4*		
Variable	*Coef*	*Std. Error*	*Prob*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*
WBL	0.0038	0.0007	(0.0000)***	0.0037	0.0012	(0.0035)***	0.0019	0.0012	(0.0059)***	0.0023	0.0012	(0.0522)*
LIT	0.0038	0.0087	(0.0000)***	0.0039	0.0090	(0.0018)***	0.0091	0.0093	(0.0060)***	0.0030	0.0083	(0.0039)***
PEM	0.3092	0.1179	(0.0087)***	0.3073	0.1227	(0.0123)***	0.2623	0.1207	(0.0290)***	0.2757	0.1200	(0.0217)**
EDU							0.2070	0.1212	0.0878	0.0994	0.9958	(0.3193)
GDP	-0.0001	6.55e-05	(0.0640)							-0.0001	6.53e-05	(0.0831)
LAB	-0.0004	0.0006	(0.0003)***	-0.0003	0.0007	(0.6796)	-0.0011	0.0008	0.1656			
Dependent Variable: DPF Method 1: Generalized Linear Model (Newton-Raphson / Marquardt steps)												
Variable	*Coef*	*Std. Error*	*Prob*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*
WBL	0.0022	0.0012	(0.0682)*									
LIT	0.0090	0.0092	(0.0061)***							0.0007	0.0098	(0.0068)***
PEM	0.2687	0.1194	(0.0245)**				0.5904	0.1173	(0.0000)***	0.5914	0.1187	(0.0000)***
EDU	0.1995	0.1200	(0.0963)*									
GDP	-0.0001	6.50E-05	0.0003	-1.19E-05	7.96E-05	0.8809	-5.67E05	7.22E-05	0.4323	-5.66E-05	7.25e-05	0.4349
LAB	-0.0012	0.0008	(0.01378)**	0.0041	0.0003	0.0000	0.0023	0.0004	(0.0000)***	0.0023	0.0005	(0.0000)***

*P-value in parentheses ***, **, * indicate significance at 1,5 and 10 % levels.*

Table 7 - Result of estimation.

Dependent Variable: DPF Method 2: Panel Least Squares												
Variable	*Coef*	*Std. Error*	*Prob*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*
WBL	0.0039	0.0012	(0.0023)***	0.0037	0.0012	(0.0043)***	0.0019	0.0012	(0.0091)***	0.0023	0.0012	(0.0551)*
LIT	0.0040	0.0089	(0.0042)***	0.0039	0.0090	(0.0027)***	0.0091	0.0093	(0.0084)***	0.0030	0.0083	(0.0000)***
PEM	0.3119	0.1213	(0.0116)**	0.3073	0.1227	(0.0139)***	0.2623	0.1207	(0.0322)**	0.2757	0.1200	(0.0237)**
EDU							0.2070	0.1212	(0.0909)*	0.0994	0.9998	(0.0018)***
GDP	-0.0001	6.58^{e}-05	(0.0684)*							-0.0001	6.53^{e}-05	(0.0862)
LAB	-0.0004	0.0007	(0.5782)	-0.0003	0.0007	(0.0005)***	-0.0011	0.0008	(0.1668)**			
Dependent Variable: DPF Method 2: Panel Least Squares												
Variable	*Coef*	*Std. Error*	*Prob*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*	*Coef*	*Std. Error*	*Prob.*
WBL	0.0022	0.00012	(0.0712)*									
LIT	0.0090	0.0092	(0.0085)***							0.0007	0.0098	(0.0070)***
PEM	0.2687	0.1194	(0.0267)**				0.5904	0.1173	(0.0000)***	0.5914	0.1187	(0.0000)***
EDU	0.1995	0.1200	(0.0099)*									
GDP	-0.0001	6.50E-05	(0.0733)	-1.19^{E}05	7.96^{E}-05	0.8812	-5.67E05	7.22^{E}-05	0.4341	-5.66^{E}-05	7.25e-05	(0.4367)
LAB	-0.0012	0.0008	(0.1409)	0.0041	0.0003	(0.0000)***	0.0023	0.0004	(0.0000)***	0.0023	0.0005	(0.0000)***

*P-value in parentheses ***, **, * indicate significance at 1,5 and 10 % levels.*

women in Africa face more inequality in education, literacy, law and employment, which hinders their ability to access digital finance. Our findings are consistent with those of (Aziz & Naima, 2021), they determine that women lack of basic connectivity, financial literacy, social awareness, and the knowledge to utilize financial services. In our case, we find novel data in digital financial services, this is related to low literacy levels in some countries as a result of socio-cultural and socioeconomic variables. We find that when the level of education increases the use of digital finance services, women who have secondary education or more use DFSs more than women who have primary education. Understanding how to use digital technologies, in this case, digital platforms and DFSs, safely, securely, and effectively is referred to as digital literacy. Our findings are supported by previous studies in the field. For example, Boileau and Yuanchen (2022) find that women face more inequality in education, which inhibits their ability to access digital finance measured by the share of women who complete upper secondary education and graduate in STEM fields respectively. We find a similar result to Khera *et al*. (2022) that women face more inequality in education, which hampers their ability to access digital finance measured by the share of women who complete upper secondary education, and graduates in STEM fields respectively. Additionally, we find that legal norms, inequality in law, and employment were identified as limitations to DFSs. We use the Women, Business, and Law Index from the World Bank to capture socio-cultural norms and legal discrimination against women. The index measures gender inequality in the law by analyzing laws and regulations affecting women's economic inclusion in the country, such as those related to mobility, labor force participation, job restrictions gender wage gap and marriage. Elouardighi and Oubejja (2023) underscore the potential of digital financial inclusion to enhance women's labor force participation in Africa, noting that access to digital finance can help overcome several barriers to employment by providing women with the tools to manage finances, access credit, and engage in business activities. Their study highlights that digital financial inclusion promotes women's economic participation by addressing issues such as limited access to traditional banking services, which disproportionately affects women in the region. Our research is similar in that it also emphasizes the importance of digital financial services (DFSs) in improving women's economic outcomes in Africa. Like Elouardighi and Oubejja (2023), we find that increasing access to DFSs can empower women by overcoming socio-economic and cultural barriers to financial inclusion. However, our study also introduces a focus on the interplay between education, legal norms, and political empowerment, further deepening our understanding of the multifaceted factors influencing women's ability to utilize fintech services in the region.

Unlike previous research, our findings demonstrate that the political empowerment of women and inclusion in the democratic decision-making process, as well as global progress toward gender equality in the law, boost the use of fintech by women. This creates more accessible financial services and promotes financial inclusion. Improving women's political engagement and representation can lead to larger societal reforms, even while the relationship between political empowerment and financial gender disparities seems complicated. Through quotas and other affirmative action policies, governments should work to achieve gender parity in political representation. Cultivating a culture of political inclusion and assisting women in leadership positions can also address underlying gender biases and establish a supportive environment for women's involvement in fintech. Building on Chinoda and Kapingura (2024), we further emphasize the importance of institutions and governance in advancing digital financial inclusion. They highlight how robust institutional frameworks and good governance practices promote trust in digital financial systems, indirectly benefiting gender equity in fintech access. Institutions with a strong commitment to inclusive policies ensure that regulatory environments are conducive to addressing disparities in digital finance access. Our study complements this perspective by showing how the empowerment of women in governance structures can further strengthen these institutional effects, advancing financial inclusion for women. Notably, this research paper is the first to highlight that when women in Africa are well-represented in political life and decision-making, gender equality is advanced, and, more specifically, African women's use of fintech is furthered.

4.3. *Robustness checks*

Despite the outputs generated by the estimation methods, we tried to extend our research beyond these results through a detailed database interpretation. To provide a more comprehensive view of gender disparities in fintech usage, this further research will look at the data. We can make more meaningful connections and tell a more complete story about the variables impacting women's adoption of fintech in Africa.

Figure 1 illustrates gender-specific disparities in the use of digital payments across African countries in 2014. Notable observations include Kenya, where both females and males exhibit high engagement in digital payments, reflecting a more inclusive adoption. South Africa also shows balanced participation between genders

Figure 1 - Financial institution account - Made or received a digital payment, female and male (% age 15+), 2014.

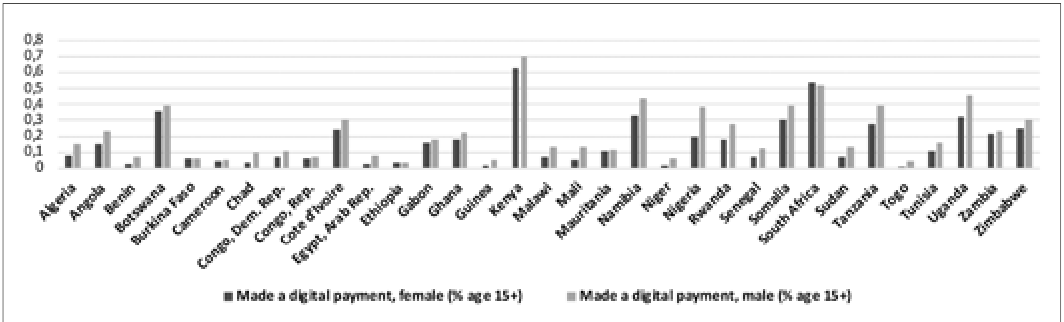


Figure 2 - Financial institution account - Made or received a digital payment, female and male (% age 15+), 2017.

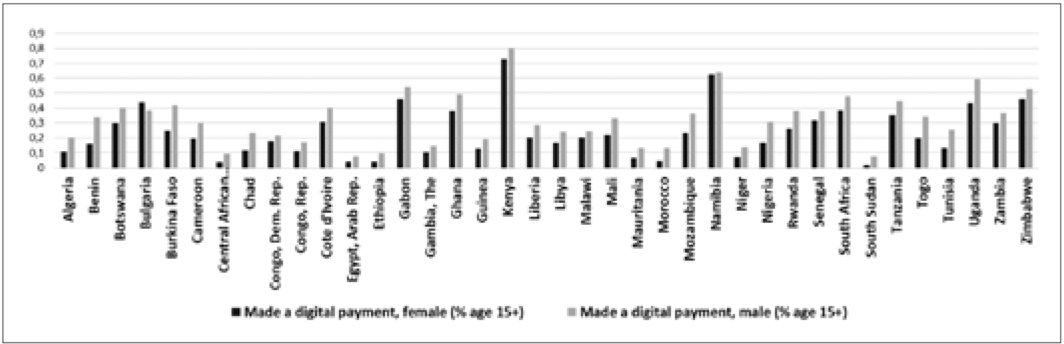
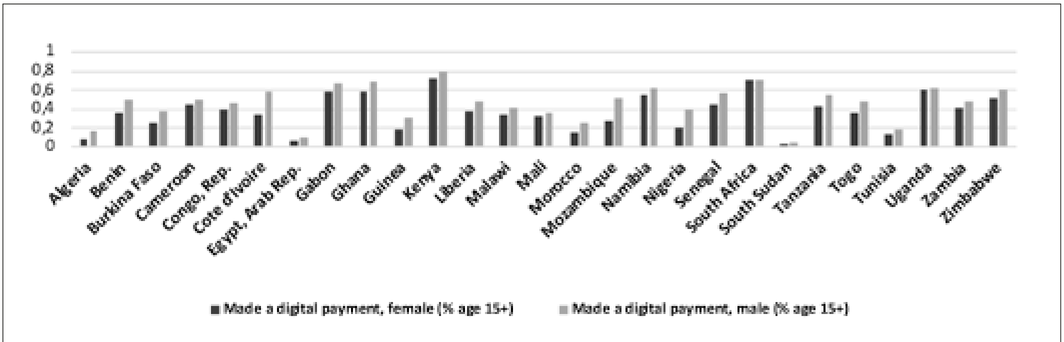


Figure 3 - Financial institution account - Made or received a digital payment, female and male (% age 15+), 2021.



but makes the exception with all other African countries where females use digital payment more than men do. However, in some countries like Togo and Guinea, the overall percentages are low, indicating a potential area for improvement in digital financial inclusion.

The variations in percentages suggest that factors such as socioeconomic conditions, cultural norms, and access to technology may influence gender-specific digital payment behaviors.

An examination of the statistics from 2014 and 2017 (Figure 2) regarding the percentage of females and males making digital payments (percentage age 15+) in various countries provides insights into the evolving landscape an overall increase in Digital Payment Adoption. The percentage of men and women who make digital payments increased overall in the aforementioned nations between 2014 and 2017.

This indicates a favourable pattern in the three-year adoption of digital financial services. There is a persistent pattern of gender inequality in both years, with men adopting digital payments at a higher rate than women in many nations. The gender difference persists despite an increase in adoption rates overall, suggesting that initiatives to close this imbalance may need to take precedence. Kenya's remarkable continuity, Kenya stands out in both years as a country with exceptionally high digital payment adoption rates for both genders. The country not only maintains its high percentages but also sees a further increase in adoption from 2014 to 2017, indicating sustained growth and acceptance of digital financial services. The usage of digital payments is generally on the rise, although gender disparities still exist. To guarantee that more people have access to digital financial services, efforts should be focused on resolving these gaps.

All figures indicate that the use of FDS by females is lower than males; the gender disparities are remarkable from 2014 to 2021.

We have noticed also, that the use of digital finance has increased from 2014 to 2021 let's take the case of Tunisia for example 14% of women used FDS in 2014 against 21% in 2021, in Alge-

Figure 4 - Financial institution account - Made or received a digital payment, primary education or less, or secondary education or more (% age 15+), 2014.

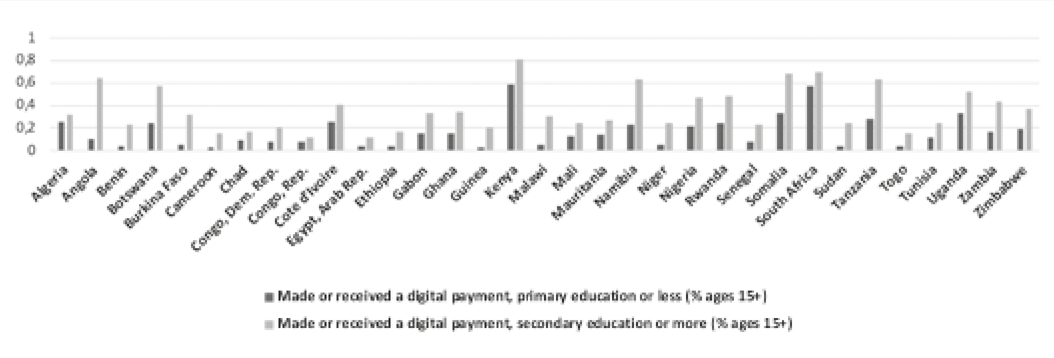
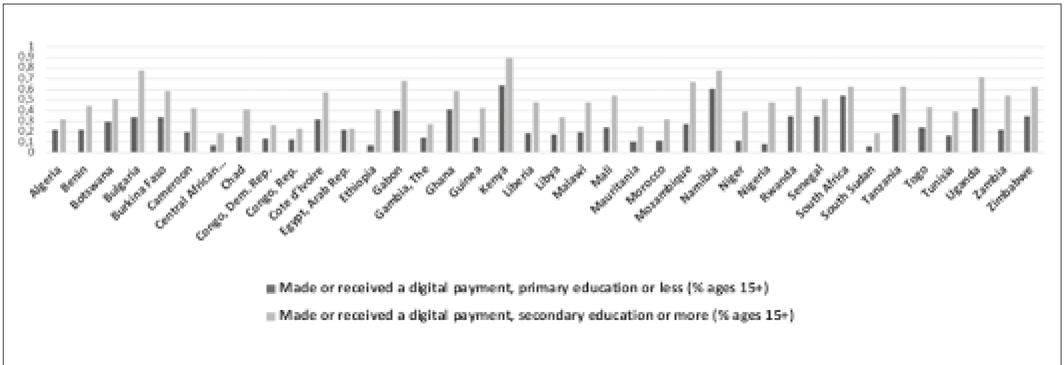


Figure 5 - Financial institution account - Made or received a digital payment, primary education or less or secondary education or more (% age 15+), 2017.

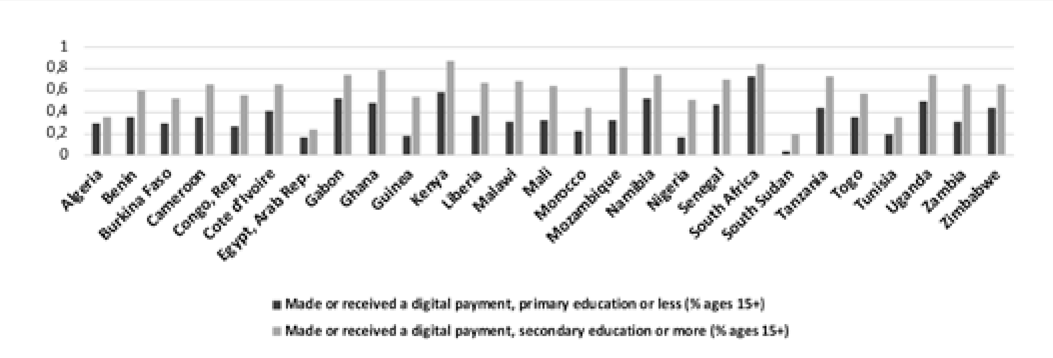


ria 19% in 2014 to 23% in 2021, in Ivory Coast, it goes from 26 % to 35%. Besides, figures show that there are differences between countries regarding the use of DFS for example we notice that in Cameroon the use of women increased from 7% in 2014 to 48% in 2021, and in Kenya also from 67% in 2014 to 74% in 2021. The gender disparity persists even in countries with high use of DFS. North African countries like Algeria and Egypt exhibit lower overall digital payment adoption rates compared to East African countries like Kenya and Rwanda. The regional context may play a role in shaping these trends. Figures show that gender disparities persist in all African countries except South Africa which makes a difference even with the increase of DFS from 2014 to 2021 the use of FDS by females is higher than by males in 2014 and it's almost equal in 2021.

Figure 4 indicate that the acceptability of digital payments throughout African countries is depicted in a variety of ways by the 2014 statistics, with usage trends indicating significant variations between individuals with only primary education and those with a secondary degree or more. Kenya boasts an exceptionally high digital payment participation rate across all educational levels, indicating a robust digital infrastructure. South Africa is another country that stands out from the rest due to its high adoption rate, whereas Cameroon and Chad have lower overall percentages. Remember that since 2014, there might have been substantial changes in the digital payment landscape, calling for a reevaluation based on more recent data to identify patterns and advancements.

The data from Figure 5 relatated to 2017 indicates a discernible increase in the use of digital payments in several nations when compared

Figure 6 - Financial institution account, Made or received a digital payment, primary education or less, or secondary education or more (% ages 15+), 2021.



to the statistics from 2014, 90% of those with at least a secondary education use digital payments, placing Kenya atop the education rankings in both categories. Other African nations including Ghana, Namibia, and Uganda are also seeing notable development, indicating that the use of digital financial services is increasing. However, there are still differences, with several countries having lower percentages, which emphasizes the need for targeted programs to raise digital literacy and accessibility. It's crucial to monitor these rapidly evolving trends and modify initiatives and regulations to support inclusive digital financial ecosystems.

The 2021 statistics (Figure 6) on the adoption of digital payments among people in different nations (% of adults aged 15 and above) and based on varying educational levels show many noteworthy trends:

Persistent Growth in Digital Payments: In 2021, the proportion of people in the aforementioned nations who make or receive digital payments increased noticeably. This points to a sustained pattern of digital financial services adoption and acceptance.

Impact of Education Level: People with secondary education or higher have a higher percentage of digital payment uptake than people with primary education or less in almost all nations. This underscores the role of education in influencing digital financial literacy and access. High Adoption in Kenya and Ghana continue to lead in digital payment adoption, with high percentages for both education groups. This suggests a robust digital infrastructure and a widespread acceptance of digital financial services in these countries. varied progress across Countries. While some countries like South Africa and Gabon show high overall digital payment adoption rates, others like South Sudan exhibit lower percentages. The variations highlight the diverse landscape of digital financial inclusion efforts across different regions. The gender disparities in digital payment adoption remain an important aspect to consider for our analysis. Despite the progress, there are still countries with relatively lower adoption rates, indicating opportunities for targeted initiatives to enhance digital financial literacy and accessibility.

Impact of the COVID-19 Pandemic (the dataset is from 2021, a period during which the COVID-19 pandemic might have influenced digital payment behaviors): The pandemic accelerated the shift towards digital transactions globally, and this data may reflect the increased reliance on digital financial services during such times.

5. Conclusion

We discover that the primary drivers of gender inequality in Africa are socioeconomic and cultural factors. Women face particular disadvantages in work, education, literacy, and legal rights, which restricts their access to fintech. Furthermore, we find that worldwide advancements in gender equality in the legal system boost women's usage of fintech, enhance the accessibility of financial services, and promote financial inclusion. Additionally, we discover that gender differences still exist throughout all of Africa, except South Africa.

This is significant since, despite the rise in DFSs between 2014 and 2021, females used FDS at a higher rate than males in three different years: 2014, 2017, and 2021. Additionally, we discover that gender differences still exist throughout all of Africa, except South Africa. This is significant since, despite the rise in DFSs between 2014 and 2021, females used FDS at a higher rate than males in three different years: 2014, 2017, and 2021. We find that the use of digital financial services rises with education level; that is, women with at least a secondary education use DFS at a higher rate than women with only a primary education. Understanding the differences in fintech among African nations is a priority for African policymakers. We also find that, except for South Africa, gender inequality persists in Fintech throughout the continent of Africa. This is noteworthy because, in three different years 2014, 2017, and 2021 females employed FDS at a higher rate than males, despite the rise in DFSs between those years. Khera *et al*. (2022) explored the gender gap of digital financial inclusion, they explored drivers of gender gap of digital financial inclusion from the side of socio-economic and cultural factors associated with law, culture and social norms unequal opportunities to work force, education and literacy, which aligns with our findings. We find that women who have completed at least secondary school are more likely to utilize DFS than women who have only completed primary school. This indicates that the use of DFS increases with education level. African authorities should prioritize learning about the variations in fintech across African countries. In addition to focusing on accessibility, affordability, safety, usability, and training of digital skills, as well as the availability of pertinent content, applications, and services, we also need to address issues of gender equality, social norms, and reforms. Furthermore, African policy makers should increase their investments in education and capacity-building initiatives that boost the digital literacy and self-assurance of women and girls. Our findings highlight the importance of legal laws in African nations that uphold and level the sociocultural norms to reduce gender differences in digital financial services. Our findings are supported by previous studies in the field. For example, Boileau and Yuanchen (2022) find that women face more inequality in education, which inhibits their ability to access digital finance measured by the share of women who complete upper secondary education and graduate in STEM fields respectively. We find a similar result to Khera *et al*. (2022) that women face more inequality in education, which hampers their ability to access digital finance measured by the share of women who complete upper secondary education, and graduates in STEM fields respectively. Moreover, we find also that legal norms, inequality in law, and employment were identified as a limitation to DFSs. We use the Women, Business, and Law Index from the World Bank to capture socio-cultural norms and legal discrimination against women. Elouardighi and Oubejja (2023) highlight the potential of digital financial inclusion to enhance women's labor force participation in Africa, emphasizing that access to digital finance can help overcome various employment barriers by providing women with the tools to manage finances, access credit, and engage in business activities. Their study underscores how digital financial inclusion promotes women's economic participation by addressing challenges like limited access to traditional banking services, which disproportionately affect women in the region. Our research aligns with this perspective, emphasizing the role of digital financial services (DFSs) in improving women's economic outcomes in Africa.

Like Elouardighi and Oubejja (2023), we observe that expanding access to DFSs can empower women by overcoming socio-economic and cultural barriers to financial inclusion. However, our study also adds a focus on the interplay between education, legal norms, and political empowerment, providing a more comprehensive understanding of the factors influencing women's ability to utilize fintech services in the region. Building on Chinoda and Kapingura (2024), we further highlight the significance of institutions and governance in advancing digital financial inclusion. They emphasize how strong institutional frameworks and good governance practices foster trust in digital financial systems, indirectly benefiting gender equity in fintech access. Institutions committed to inclusive policies create regulatory environments conducive to addressing disparities in digital finance access. Our research builds on this by showing how women's empowerment in governance structures can further strengthen these institutional effects, enhancing financial inclusion for women. Notably, this paper is the first to demonstrate that increased female representation in political life and decision-making not only advances gender equality but also promotes greater adoption of fintech services among African women.

Our contribution to this research is the conclusions we draw, which show that women's usage of fintech is enhanced and financial inclusion is promoted when they are included in political empowerment and democratic decision-making processes. We believe that more research should be done on how to close the gender gap, with a special emphasis on the case of South Africa, which is the only African nation where women used FDS more than men in 2014 and nearly equally in 2021. Other research should also look at how Fintech is affecting SDG, how to increase the representation of women in politics, and what factors contribute to the gender gap in Fintech in African countries.

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Appendix 1 - List of countries included in the sample

N°	*Country*	*N°*	*Country*
1	Algeria	19	Mauritania
2	Benin	20	Morocco
3	Botswana	21	Mozambique
4	Burkina Faso	22	Namibia
5	Cameroon	23	Niger
6	Central African Republic	24	Nigeria
7	Chad	25	Rwanda
8	Congo, Dem. Rep.	26	Senegal
9	Congo, Rep.	27	South Africa
10	Cote d'Ivoire	28	Tanzania
11	Egypt, Arab Rep.	29	Togo
12	Ethiopia	30	Tunisia
13	Gabon	31	Uganda
14	Ghana	32	Zambia
15	Guinea	33	Zimbabwe
16	Kenya	34	Mali
17	Liberia	35	Malawi
18	Libya		

To what extent the non-extension of the Black Sea grain deal is disrupting global and Arab wheat markets

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Abstract

The ongoing conflict between Russia and Ukraine has significantly affected the global wheat market, particularly impacting Arab countries that heavily rely on wheat imports. This paper examines the conflict's effects on wheat production and exports, highlighting disruptions in Ukraine and the resulting price volatility. Together, Russia and Ukraine account for a large share of global wheat exports, but the conflict has led to a decline in Ukrainian exports, mitigated somewhat by the Black Sea agreement which allowed for continued exports despite Russian sanctions. As major exporters like the U.S., Canada, and Australia step in, competition has intensified, leading to fluctuating prices. This volatility threatens food security and fiscal stability in Arab nations, especially those with limited or no wheat subsidies. The study suggests that the nonrenewal of the Black Sea agreement could raise global wheat prices by 3-4% on average, though the overall impact is expected to be short-lived due to the market's resilience. The findings emphasize the need for proactive import planning and highlight the importance of agricultural policies and trade finance in shaping wheat market dynamics.

Keywords: *Food security, Wheat, International trade, Arab countries.*

1. Context and objectives

Wheat is one of the most crucial cereals grown worldwide, ranking third in terms of production (WEF, 2022)[1]. On average, one quarter of global wheat production is exported worldwide. However, and since decades, the global market of wheat has been characterized by volatility often limited but sometimes very high reflecting unusual conjunctures and crises. The global population continues to grow, and this increase is accompanied by rising food demand, particularly in developing countries where agricultural production does not keep pace with population growth. This situation makes the food system dependent on the international market, which has become increasingly unstable with significant price volatility (Harbouze *et al.*, 2024). In general, wheat price volatility often reflects uncertainty over the continuing flow of suppli-

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[1] https://www.weforum.org/agenda/2022/08/top-10-countries-produce-most-wheat/.

ers, which itself depends on a number of factors, mostly current production and available stocks (IFPRI, 2023). However, it could be also the direct effects of severe supply chains disruption mainly due to conflicts and weather conditions.

The Russia-Ukraine war triggered a wave of shocks in international energy and agricultural markets due to the significant role these two countries play in these strategic sectors. Together, Russia and Ukraine account for one-third of global wheat exports, 80% of sunflower oil exports, and 20% of barley and maize exports (Abis and Demurtas, 2023). However, the price volatility observed in the first months following the outbreak of the conflict was not driven by a decline in global production. Instead, it stemmed from difficulties in shipping Ukrainian and Russian cereals across borders, compounded by speculation and public interventions aimed at capitalizing on the crisis. This is evidenced by the fact that prices quickly returned to pre-crisis levels—or even lower—immediately after the grain deal between Ukraine and Russia was brokered by the UN and the Turkish government. One year after the agreement was signed, the situation has reverted to its pre-deal state as Russia has refused to renew the agreement. This has reignited speculation, particularly during a critical period when exporting countries are finalizing new deals. These developments have once again heightened uncertainty about the future trends in global wheat prices, raising questions about whether prices will continue to rise or decline, and under what conditions such shifts might occur.

The purpose of this paper is an attempt to investigate the sources of the volatility of world wheat prices and to determine the winners and those who suffer from this volatility. It starts by looking at the major players in the global wheat trade market prior to the conflict. Subsequently, it analyses the impact of the war on Ukraine's and Russia's wheat sectors compared with the situation prevailing the conflict. Third, it looks to the winners and losers from the crisis before and after the implementation of the Black Sea Grain Initiative (BSGI), which was signed in July 2022 between Russia and Ukraine under the auspice of Turkey and the UN but unfortunately not renewed since July 18, 2023. Finally, the paper provides the results of some simulations regarding the short-term trends of global wheat prices under alternative scenarios on the perspectives of exporting wheat from both Ukraine and Russia.

2. Overview of world wheat market

2.1. *Recent World Wheat price volatility*

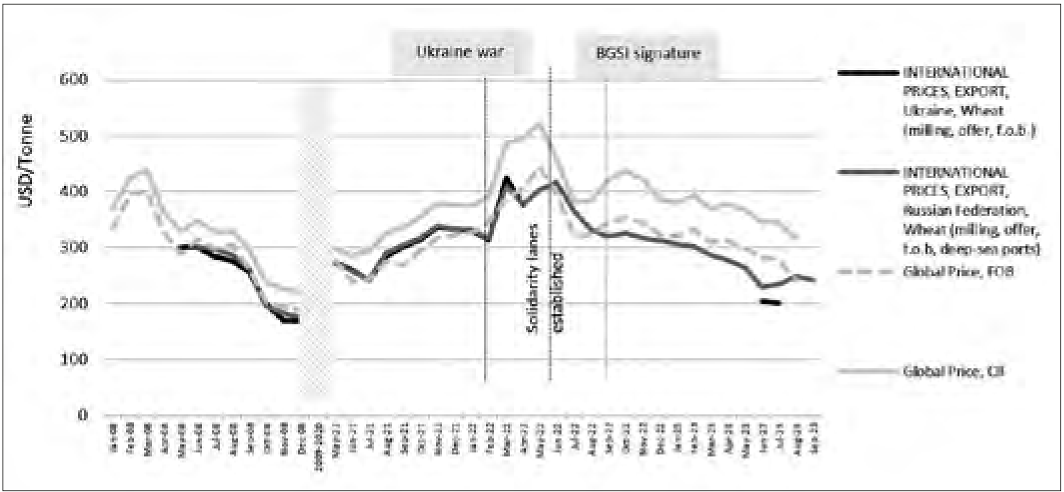
In May 2022, three months after the start of the Ukraine-Russia war, global wheat prices reached all-time highs of 522$ per ton (CIF) and 444$/ton (FOB) (Figure 1). However, two months later, world prices fell significantly even before the conclusion of the wheat deal on exporting Ukrainian wheat. This tendency confirms once again the importance of the anticipation effect and that the rush of importing countries to secure wheat was accelerated during the first two months after the war. However, data shows that no major shortage of wheat supply was observed since February 2022 but just a re-shifting of directions of trade in favour of most of exporting countries, except Russia and Ukraine.

2.2. *World Wheat market: major players in the pre-conflict phase*

The key wheat producers are China, India, the European Union, the United States, Russia, and Ukraine with a total share in global production of 69.8% in 2021 compared to 70.9% in 2008 (Figure 2).

Similarly to production, the EU, Russia, United States, Australia, Canada, Ukraine, and Argentina form the bulk of global export of wheat. Between 2010 and 2021, they accounted for more than 90% of global wheat export. Both of the Black Sea region countries, Russia and Ukraine made up about 26 percent of the 198 million tons globally exported wheat in 2021 (figure 3). The Arab region, EU27, Africa, Indonesia, China, and Turkey are heavily reliant on wheat imports, making them the most vulnerable to fluctuations in global wheat prices (figure 4).The European Union is one of the world's top producers, exporters, and importers of wheat. France, Romania, Germany, and Poland make up about 73% of the wheat exported by the EU to the rest of the

Figure 1 - Recent trend in global wheat prices, CIF and FOB basis.



Source: Global Price FOB, IMF commodity prices. Global Price CIF, World Bank Commodity Price Data (the Pink Sheet) Russia and Ukraine, FAO, FPMA Tool, available at https://fpma.fao.org/giews/fpmat4/#/dashboard/tool/international.

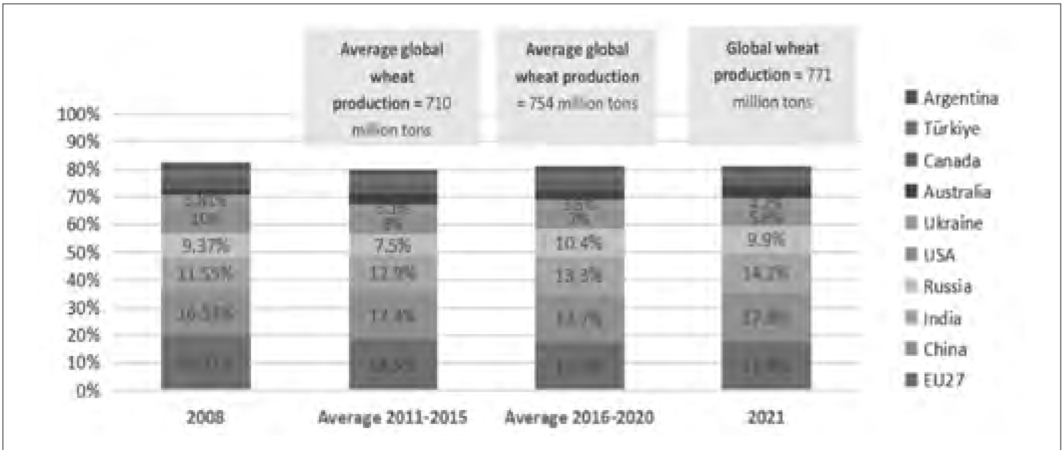
world. Dependency on extra-EU wheat import is falling since 2010, only Slovenia is reliant on wheat imports from extra-EU partners, followed by Ireland and Croatia. Most of the EU's member countries continue to rely on imports from their union's partners.

To a large extent, the development of the EU's wheat export potential is attributed to the financial support provided through the Common Agricultural Policy since its adoption in 1962.

The Arab region is the largest regional importer of wheat, consistently absorbing a significant share of global exports. In 2021, approximately 19% of the world's wheat exports were directed to the Arab region. On average, Arab countries received 21.5% of total global wheat exports during the period 2016-2020, reflecting a decline of about 2.7 percentage points compared to the 2011-2015 period (Figure 4).

In 2021, the top regional wheat buyers exhibited varying degrees of reliance on their main suppliers. The Arab region primarily depends

Figure 2 - Top wheat producers, as a share of global production.



Source: FAOSTAT, 2023. Available at https://www.fao.org/faostat/en/#data

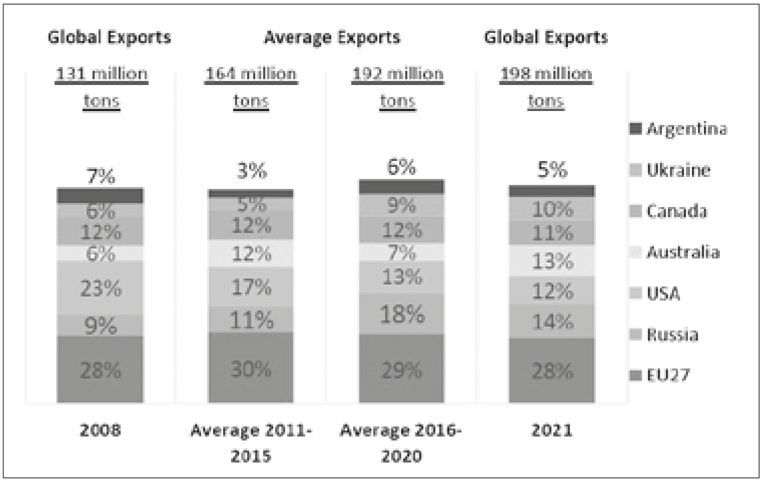


Figure 3 - Main wheat suppliers, shares of global exports.

Source: FAOSTAT, 2023. Available at https://www.fao.org/faostat/en/#data.

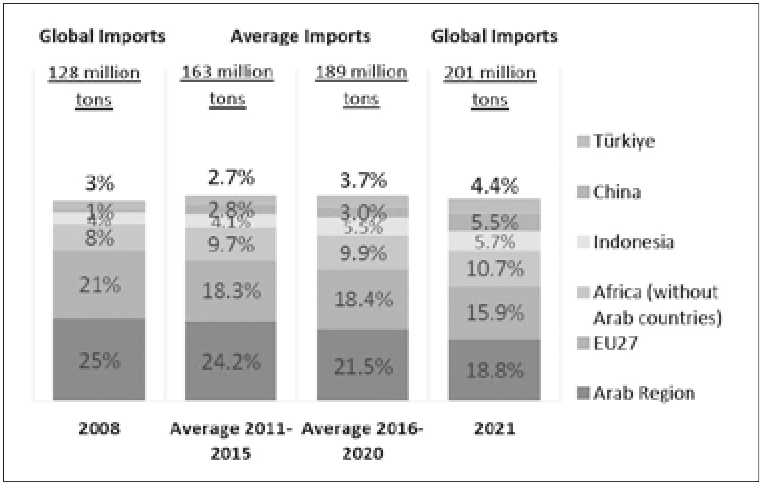
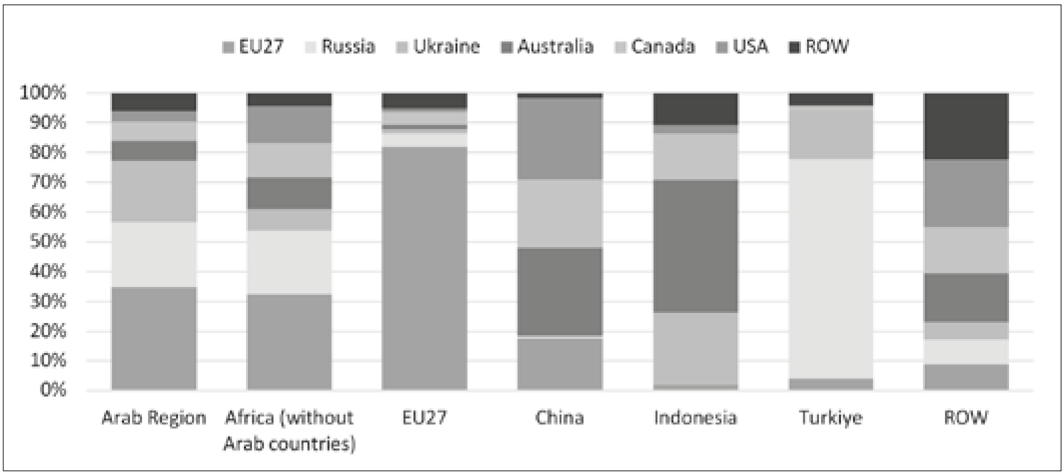


Figure 4 - Main wheat buyers, shares of global.

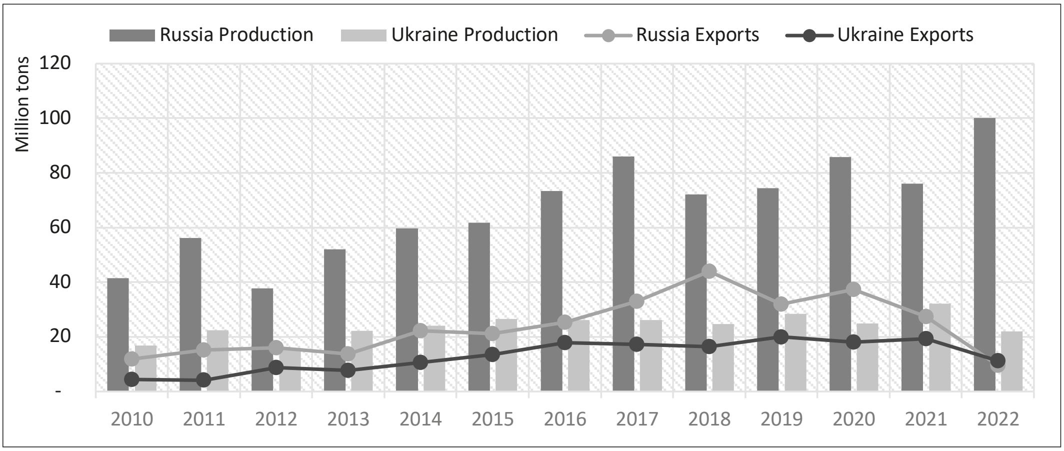
Source: FAOSTAT, 2023. Available at https://www.fao.org/faostat/en/#data.

Figure 5 - Major Wheat importer's share from main origins, 2021.



Source: FAOSTAT, 2023. Available at https://www.fao.org/faostat/en/#data.

Figure 6 - Russia and Ukraine wheat production and exports, 2010-2022.



Source: FAOSTAT, 2023. Available at https://www.fao.org/faostat/en/#data.

on three key sources: the European Union (EU), Russia, and Ukraine. Similarly, Sub-Saharan Africa relies on the EU and Russia, albeit to a lesser extent on Ukraine (Figure 5).

3. War and wheat: Ukraine and Russia's wheat trade reshaped

Given their position in the wheat market, evidenced by their increasing market shares, production, and export volumes (Figure 6), Ukraine-Russia conflict undoubtedly influenced global wheat supply and prices. When considering export-to-production ratio, Ukraine outperforms Russia, highlighting the significance of Ukraine's wheat sector and its contribution to global markets.

Closure of all Ukrainian Black Sea ports, which account for roughly 90% of Ukraine's wheat exports (World Bank, May 2022) surely posed challenges to wheat exports to partner countries. Nonetheless, Ukraine's borders with neighbouring countries such as Poland, Hungary, Romania, and Slovakia serve as important transit points for trade in goods, including wheat. Even after the Black Sea Grain Initiative, which was specifically established to open Ukrainian sea ports, lower food prices, and ensure shipments to the rest of the world, particularly poor and developing countries in Asia and Africa, figure shows that the country's exports remain very low compared to total world exports.

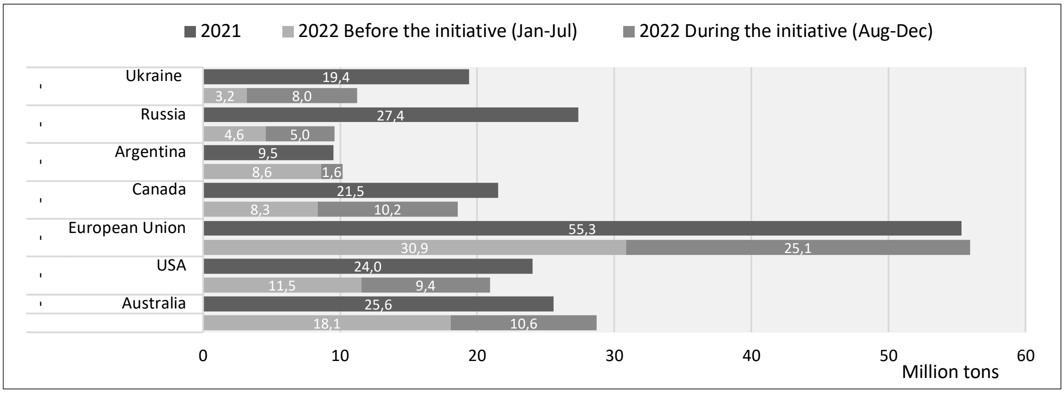
To facilitate exports of Ukrainian wheat, the

Table 1 - Neighboring Eastern European countries' wheat import from Ukraine, 2021 vs 2022.

Means of transport	*Reporter*	*Qty in tons 2021*	*Values 2021*	*Qty in tons 2022*	*Values 2022*
Rail	Hungary	..	..	153,579	$ 39,457,284
	Poland	..	..	335,499	$ 76,649,615
	Romania	..	..	101,195	$ 26,547,299
	Slovakia	..	..	45,741	$ 11,391,056
Road	Hungary	65	$ 25,301	35,180	$ 9,341,769
	Poland	3,118	$ 1,042,017	187,332	$ 44,083,666
	Romania	..	..	217,848	$ 54,107,128
	Slovakia	..	..	26,616	$ 7,562,982

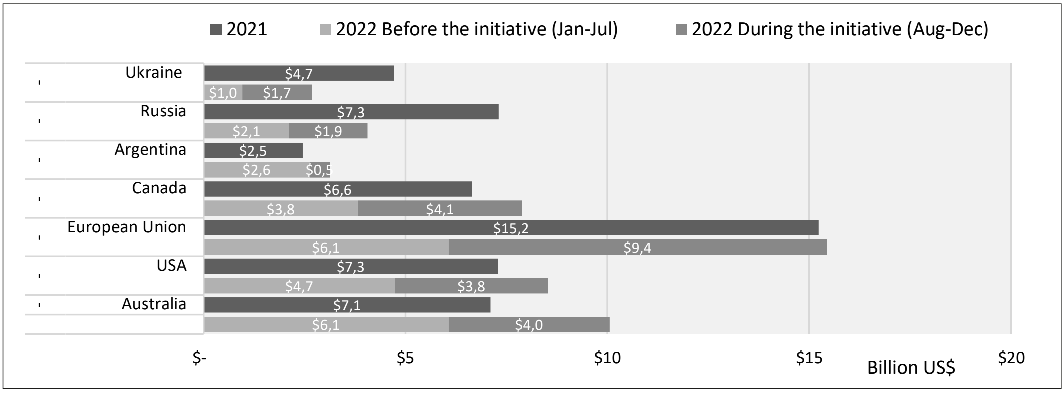
N.B. (..) means no imports were recorded.
Source: Eurostat, 2023. Available at https://ec.europa.eu/eurostat/web/main/data/database.

Figure 7 - Wheat exports by main origin in volume (in millions MT), 2021 vs 2022.



Source: COMTRADE monthly data for Wheat and Meslin (HS 1001). Available at https://comtradeplus.un.org/TradeFlow.

Figure 8 - Wheat exports by main origin in values (in billion US$), 2021 vs 2022.



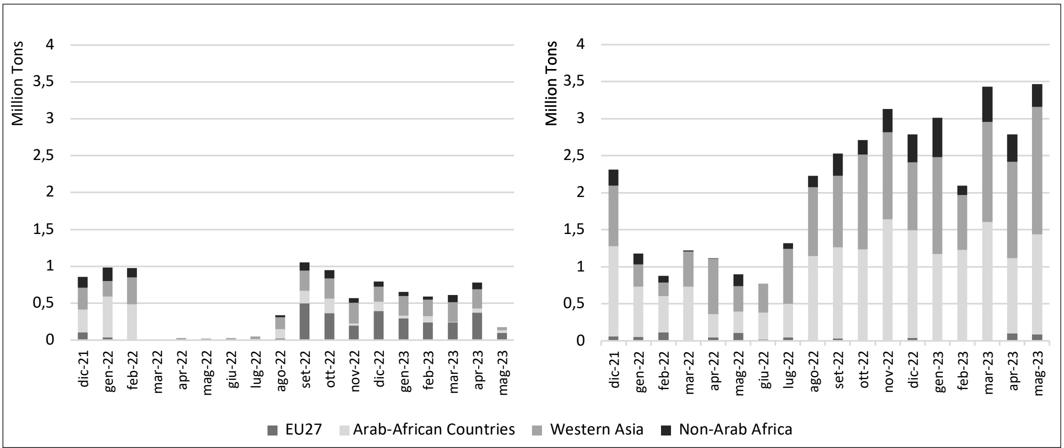
Source: COMTRADE monthly data for Wheat and Meslin (HS 1001). Available at https://comtradeplus.un.org/TradeFlow.

EU decided in June 2022, few days before the dead sea agreement, to remove all tariffs and quotas on grain imports from Ukraine. As a result, and according to the available data, the Eastern European countries, traditionally net grain exporters, imported unprecedented amounts of wheat by road and rail in 2022 (Table 1). While in 2021, only Hungary and Poland imported very small volume of wheat from Ukraine. In 2022, the picture changed completely, and the four neighbouring countries, namely Hungary, Poland, Romania and Slovakia, imported around 1.1 Millions MT compared to only 3183 Metric Tons one year before, which represented around 3% of total wheat exports of Ukraine in 2022.

Monthly wheat maritime export data from WTO Global Trade Data Portal[2] shows that Ukraine exports ceased between March and July 2022, then

[2] This dashboard, developed jointly by the International Grains Council (IGC) and the World Trade Organization, offers a tool for monitoring short-term trends in international wheat maritime trade flows in response to changing market conditions and enables the analysis of longer-term trends. Available at https://globaltradedata.wto.org/real-time-data-based-on-non-wto-data-sources. Since Arab region is not exclusively mentioned, data for Western Asia (Bahrain, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, Georgia, Israel, and Türkiye) can somehow reflect trade with Arab countries which constitute the biggest part of the Western Asia region. As for Northern Africa, it includes African-Arab countries (Algeria, Egypt, Libya, Morocco, Sudan, and Tunisia).

Figure 9 - Ukraine (left) and Russia (right) monthly wheat maritime exports to selected areas, 2021-2023.



Source: WTO, Global Trade Data Portal, 2023. Available at https://globaltradedata.wto.org/real-time-data-based-on-non-wto-data-sources.

began to increase again in August with the resume of trade under the initiative but remain lower than pre-war levels. The graph shows that wheat exports to the European Union have increased since the initiative compared to pre-war levels while its exports to Northern Africa have decreased. Russia's wheat maritime exports on the other hand were more diverse pre-war than post-war, but exports to Western Asia and Northern Africa were still the highest among other regions during both periods. During the first few months of the war, its exports certainly decreased but the country still exported wheat (Figure 9).

According to UNCTAD report[3], the least-developed countries received the smallest share of wheat export from Ukraine under the initiative (20%), with developing countries receiving the lion's share (45%), and developed countries receiving 34%. In terms of income levels, high-income countries had the highest share (37%), followed by low-income countries (10%) and lower-middle-income countries (33%). At first glance, European wheat exports have increased since the start of the war. Northern Africa is the biggest importer during the period July 21-May 23. The highest quantity ex-

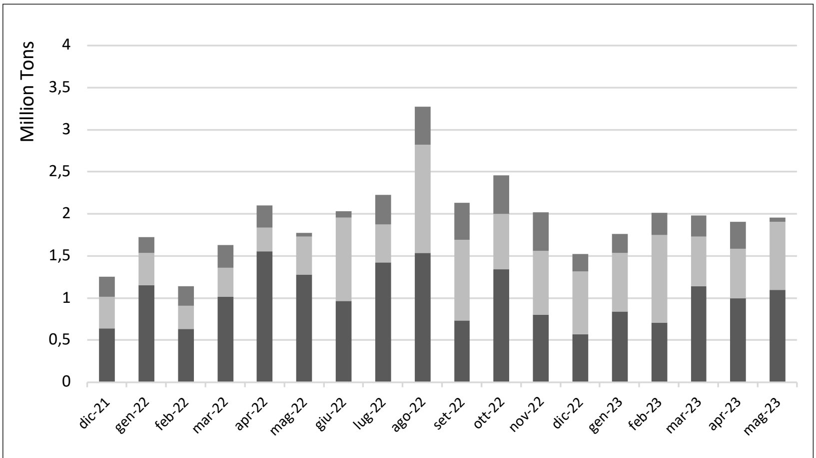


Figure 10 - Monthly European Union wheat maritime exports to selected areas.

Source: WTO, Global Trade Data Portal, 2023.

[3] https://unctad.org/system/files/official-document/osginf2023d3_en.pdf.

ported was during Aug-22, the month where the first wheat trade was launched under the BGSI initiative (Figure 10).

4. The determinants of world wheat prices

There are four major direct factors that affect world prices of wheat namely: yield and global production, global consumption, global trade, and transactions costs (transport and insurance fees). However, agricultural policies are also an important incentive but also distorting factor widely used in the world but mainly in the EU and USA. They affect all channels of the global supply chains starting from production, consumption, and transport. The EU and USA's agricultural policies played a significant role in blocking any significant progress on multilateral liberalization of agricultural trade under the Doha round and even the full implementation of the partial agreement reached in 2015 on reducing distortive subsidies. Accordingly, the global wheat market still largely impacted by these supporting policies. In addition, international embargo on trade with and from specific countries, such as the case of Russia, is also disturbing international trade of key commodities such wheat, oil and gas. Below we briefly highlighted the role of these factors in global wheat market.

Distortive trade policies

Since decades, most developing countries over the world started the implementation of sectoral support programs in favour of their agricultural sectors. The most important programs were designed and implemented by the USA and the EU. While the original farm bills were enacted during the 1930, the first Common Agricultural Policies of the European countries was enacted in 1962. The 2018 Farm Bill was projected to cost about $428 billion over the five years of the bill's life, which represent around 50% of total agricultural GDP in 2018-2022, which is too high by international standard. There are three major groups of entitlement programs under the bill namely commodity, crop insurance and nutrition assistance. The new adopted CAP 2023-2027 will cost 307 Billion of Euro, 264 from the EU resources and 39 from public expenditures. CAP resources represented around 34% of Agricultural GDP in the EU, which is lower than the USA, but still too high compared to public support of agricultural sector in developing countries which is always below 1 to 2%.

The debate on the distorting effects of agricultural policies in the USA and EU is not new and several studies pointed out the adverse effects on competitiveness of agricultural sectors in developing countries largely impacted by artificial and low world prices of major crops such as wheat. While negotiations under the WTO since its creation in 1995 did not stopped on unlocking the uncompetitive of the agricultural world markets and its negative effects on farmers' incomes in developing countries, progress towards reaching an ambitious agreement under the Doha round on putting agricultural trade under WTO's rules still not be achieved despite intermediary agreements on export subsidies and switch of support funds among boxes. Moreover, it is highly believed that any increase in world wheat prices is a positive channel for reducing financial burdens on the EU's budget.

Volatile transport and insurance costs

In general, transport and insurance cost represent an important factor of world prices through its effects on countries' competitiveness in the global markets. According UNCTAD (2022), the grain shipments over longer distances are leading to higher food prices. It shows that grain prices and shipping costs have been on the rise since 2020, but the war in Ukraine has exacerbated this trend and reversed a temporary decline in shipping prices. The report says between February and May 2022, the price paid for the transport of dry bulk goods such as grains increased by nearly 60%. The report estimates that the accompanying increase of grain prices and freight rates would lead to a 3.7% increase in consumer food prices globally in 2022, of course for countries without inforce consumer subsidies programs.

These costs are intensified by the trade sanctions imposed by the EU and USA on Russian exports. While officially, sanctions imposed by the EU and others excluded the agricultural sector, adverse effects posed some challenges to trade with Russia. For instance, sanctions on bank-

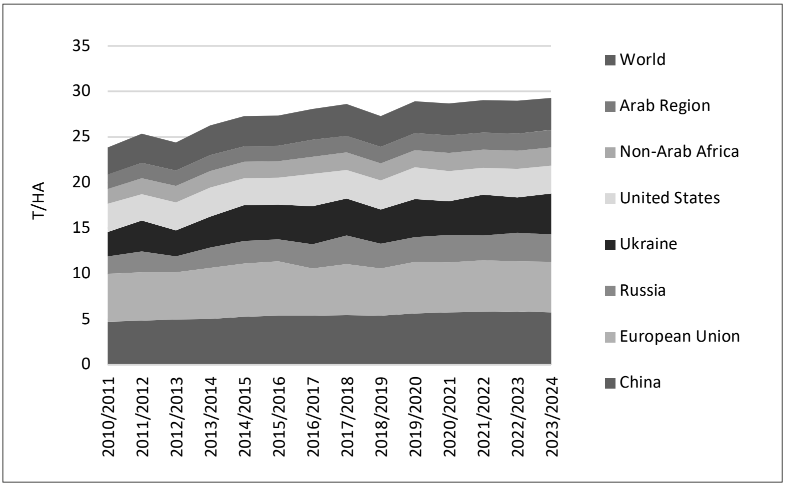


Figure 11 - Average wheat yields of selected areas, 2010-2023.

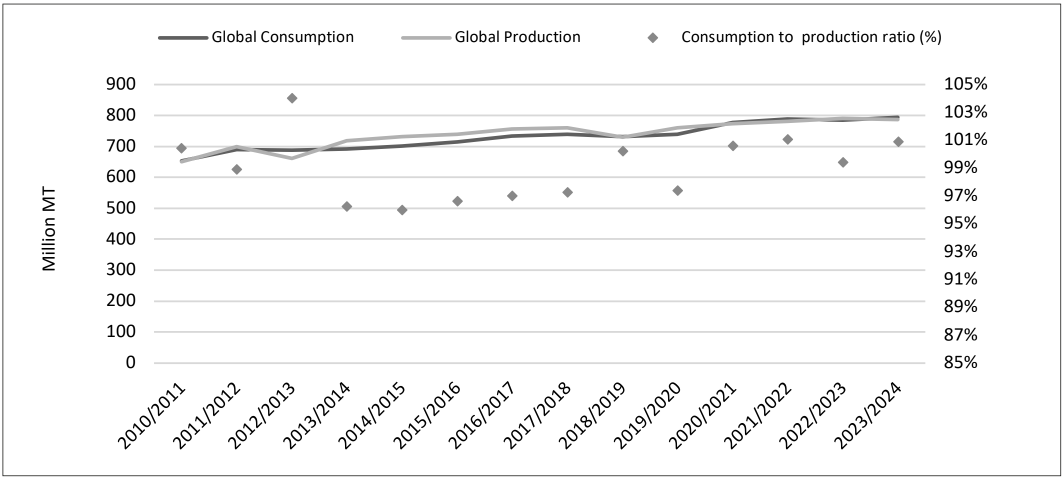
Data Source: USDA FSA PSD Database and aei.ag calculations.

ing and individuals has made trade with Russia more costly and risky.

Wheat's yields and increasing gaps between global production and consumption

Recent decades have seen wheat yields stagnate globally. Despite that current rates of yield increase, associated with genetic improvement, but they are still not sufficient to meet the increase in wheat grain demand expected by 2050 particularly considering the expected demand growth in Asia and Africa. For 2023/24 global wheat production is forecasted at a record 800.2 million metric tons (MMT). This upward revision is a result of larger crops for Russia, India, the European Union (EU), and Ukraine. At the same time, the 2023/24 global wheat consumption is estimated to increase by 3.5 MMT to 793.1 MMT, driven by higher feed and residual consumption. Thus, the gap between production and consumption still positive but decreasing which give a small flexibility in countries with significant storage capacities such as EU, USA and India. The declining surplus of wheat production is a key factor affecting the vulnerability of global wheat market which makes it very sensitive to any change affecting the global supply of wheat.

Figure 12 - Global wheat consumption and production, 2010-2023.



Data Source: USDA FSA PSD Database and aei.ag calculations.

5. How the non extension of the cereals' deal may affect the global wheat market world prices: an application of partial spatial equilibrium model on wheat market

The invasion in February 2022 led to a complete halt of maritime grain shipments from Ukraine crisis, through facilitating the shipment of Ukrainian cereals, indirect discussions began between Russia and Ukraine in April under the support of Turkey and the UN. An agreement was signed in Istanbul on 22 July 2022, for a period of 120 days. The original agreement was set to expire on 19 November 2022. On 17 November 2022, the UN and Ukraine announced that the agreement had been extended for a further 120 days then for another 60 days. In May 2023, the deal was once again extended for 60 days, expiring on 18 July. By July 17, 2023, no new agreement to renew the deal had been reached, causing the deal to expire. Using a spatial partial equilibrium model, the future of the global market of wheat is evaluated under two scenarios assuming the non-renewal of the black see agreement. The features of the model, the tested scenarios and major results are explained in the next sections.

5.1. *The model*

The model used in this study is a nonlinear mathematical programming model under nonlinear constraints. More specifically the model is a partial equilibrium which reproduces the economic equilibrium based not only on the prices and the quantities produced, consumed, and traded for each country and region individually considered in the model, but also on the trade flows for each couple of countries and regions between them. Indeed, when we are interested to a particular product with a relatively small contribution to the national GDP. It's not justified to use general equilibrium models because their main advantages are to capture the interactions among different economic institutions, sectors and factors of production. Sectoral models are more appropriate for analysing policies affecting a particular sector, such as the wheat sector. In addition, a sectoral or partial model is the most appropriate tool given its capacity to take into account the interactions between the markets for the concerned product in the countries and regions of the world.

Unlike the non-spatial partial economic equilibrium model, a model like the one used in this study for the analysis of discriminatory trade policies, is able to integrate the different features of trade policies in addition to other policies affecting both production and consumption. Furthermore, by analysing the policies affecting a given product and sector we can evaluate the prospects and features of trade flows among countries and regions but also the impacts on domestic production and consumption and their respective prices.

The model used here considers only one product, wheat. At the production stage, wheat is considered as an aggregate product covering both soft and durum wheat. In the consumption stage, we consider the different uses of soft and durum wheat products as wheat equivalent quantities. Moreover, the wheat product is considered as a perfect homogeneous product. Due to its nature, exchange rates are fixed by assumptions (all the levels they had during the reference baseline). Except for the distortions due to the explicit policies considered in the model, we assume that conditions of perfect competition exist in the markets which take place whether within each country or for each pair of countries. Transport and insurance costs are also fixed by assumption based on the observed trend for the year 2021 and 2022 and forecasts for 2023 and 2024.

The model is directly based on the prototype proposed by Takayama and Judge (1971) that has been applied to different sectors and countries. It's also based on the model version developed by Anania and Chemingui (1997) for the analysis of Euro-Med trade integration for the case of wheat. The model maximizes an article objective function of non-linear quasi-welfare subject to linear and nonlinear constraints. It considers individually 18 countries and regions including 5 Arab countries. The list covers also major exporters and importers of Wheat in the world including both Ukraine and Russia. The countries and regions considered are the following: Morocco, Algeria, Tunisia, Egypt, Jordan, EU 27, USA, Canada, Argentina, Australia, China, Russia, Ukraine, Inia, Pakistan, Rest of Asia, Rest of Africa, and rest of the world.

The model is calibrated using data for the year 2021, which represent the year preceding the start of the war between Ukraine and Russia and therefore it reflects a situation of equilibrium or reference scenario of the wheat market. The major information source for the model's database is FAO (2023b). The second source of information used for the model is the International Grains Council, specifically for data unavailable in the FAO database. Accordingly, the data source for production and consumption values of wheat by country and region, as well as producer prices, was the FAO. Consumer prices, on the other hand, were drawn from various sources, primarily the retail price of bread in different countries as documented in the International Grains Council publications (IGC, 2023). These bread prices provided insights into inter-country price variations and facilitated the estimation of consumer prices for wheat-based products.

Price elasticities of production and consumption functions were derived from estimates by Chemingui and Anania (1997), Piggot and Fisher (1993), Tyagi (1993), and Iqbal and Babcock (2016). Regarding transportation and handling costs between countries (from border to border), a key assumption was that these costs are symmetric. The matrix of transportation costs between countries was obtained from the International Grains Council.

5.2. *Scenarios*

The reference scenario

The model is calibrated and solved for the period 2021-2024. The baseline scenario assumes the continuity, business as usual, for the wheat sector and most important policies affecting production, consumption, and trade for each country and region. The calibration is based on available data for 2021, 2022 and 2023 as well as latest forecasts for the years 2023 and 2024. However, the baseline scenario assumes the renewal of the black see agreement on Ukrainian exports for Wheat. The baseline scenario therefore allows us to analyse the outlook for the wheat sector in the absence of other external or exogenous shocks in the form of new trade agreements or revised policies affecting both production and consumption of wheat over the world. Thus, it reflects the scenario of normal and continued development of the wheat sector in each country and region individually considered in the model.

Alternative scenarios

Compared to the reference scenario, which stipulates the renewal of the Black Sea agreement on Ukrainian crops exports, two alternative scenarios were tested. The first assumes the non-renewal of the agreement which directly leads to the blocking of grains export from Ukraine through the black sea, As a result, Ukrainian exporters will use alternative routes to reach their major customers without any flexibility from the EU countries regarding tariffs concessions and preferential access that could be granted to Ukraine during the time of the crisis. Thus, the majority of exports will be carried out through multi-mode transport channels (road, railways, river) that are used as a transit routes facilitating the Ukraine's exports outside the EU countries.

Several assessments have shown that the alternative export routes are costly for Ukraine's exports, which will reduce their competitiveness on world markets. Available information confirms that an increase in transport costs of Ukrainian cereals may reach between 20 to 50% compared with the cost of shipping through the black sea. The second scenario assumes a non re-renewal of the black sea agreement but with a complete opening of the European market to Ukrainian exports which could partially compete with the European producers and consequently benefit from certain support instruments of the CAP even an indirect way.

Impacts

The impacts of the first scenario show increase of producer prices both in importing and exporting countries that do not subsidize their exports or their producers or consumers. For the EU, the producer price increases significantly compared to the reference scenario to reach 6% in 2023 and 8% in 2024. At the same time, consumption falls but exports increase to all destinations considered in the model. Due to the rigidities in the supply functions to reflect the projected yields in 2023 and 2024, the increase in producer prices will generate a small increase in production which will not exceed 2% in 2023 and 3% in 2024. For the USA, the impact of the first scenario is a sharp increase in the producer price of wheat driven by an increase in foreign demand and a stagnation of domestic production and consumption in the USA. The result is an increase of the UAS's exports of wheat by respectively 5 and 6% in 2023 and 2024. A significant share of the USA's increase of wheat exports is through using existing stocks, which are taken into account in the model.

The changes in market shares of major wheat exporters due to the first scenario is reflected by an increase of total exports of all of them, except Ukraine and Russia. Consequently, and as expected, the immediate effect is a significant increase of world prices of wheat as well as consumer prices in most countries around the world. Exports from Ukraine and Russia are increasingly used to regulate stocks or in some case to immediately satisfy shortages in many poor and less developing countries mainly in Africa and the Arab region, However, and compared to the reference scenario, total world exports under the first scenario will represent around 95% of total exports in the reference scenario. The deficit or gap in wheat supply is largely covered by national stocks but also through a significant reduction of domestic consumption of wheat and its derivatives in many countries around the world and particularly in the poorest among them. The drop in domestic consumption in most developing countries are even intensified by the significant devaluation of national currencies. These impacts are further intensified by the declining fiscal spaces for many developing counties that make the implementation of adjustment and support mechanisms for the most vulnerable populations a difficult task.

For the five Arab countries considered in the model, the impacts are also different and depend largely on the economic policies followed by each of them. Thus, Algeria and Tunisia will have

Figure 13 - Impacts on Producer prices.

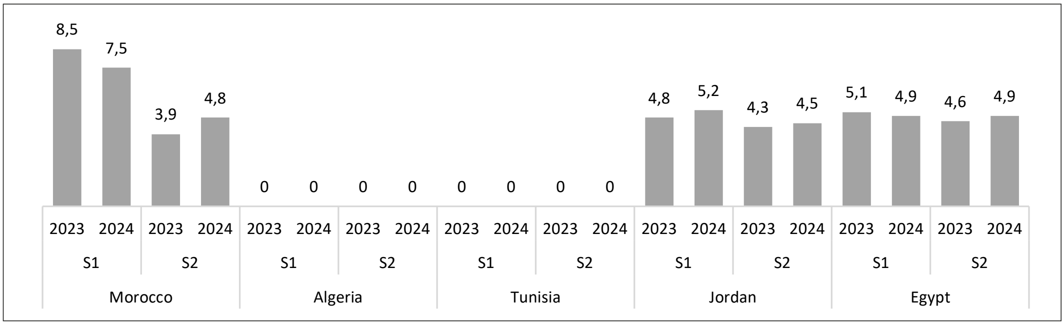


Figure 14 - Impacts on Consumer Prices.

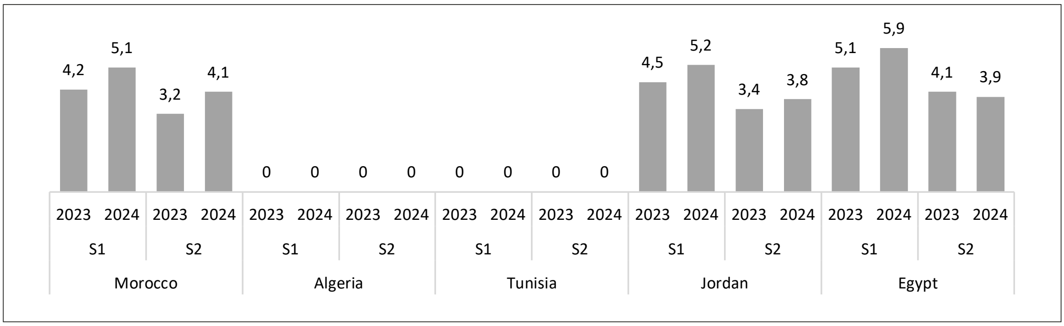


Figure 15 - Impacts on Production (volume).

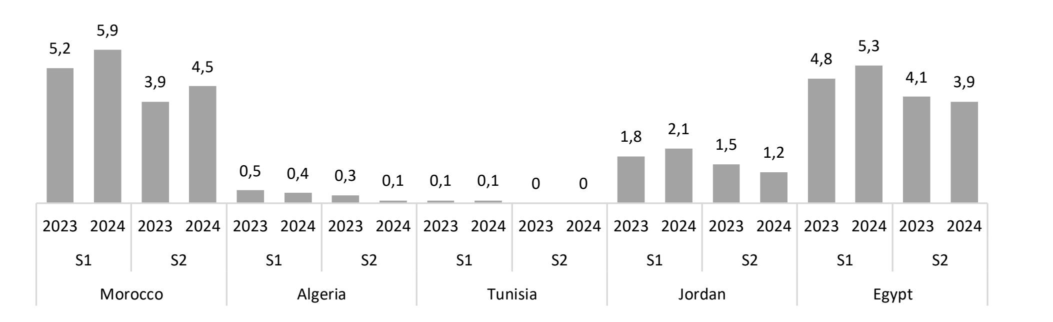


Figure 16 - Impacts on consumption (volume).

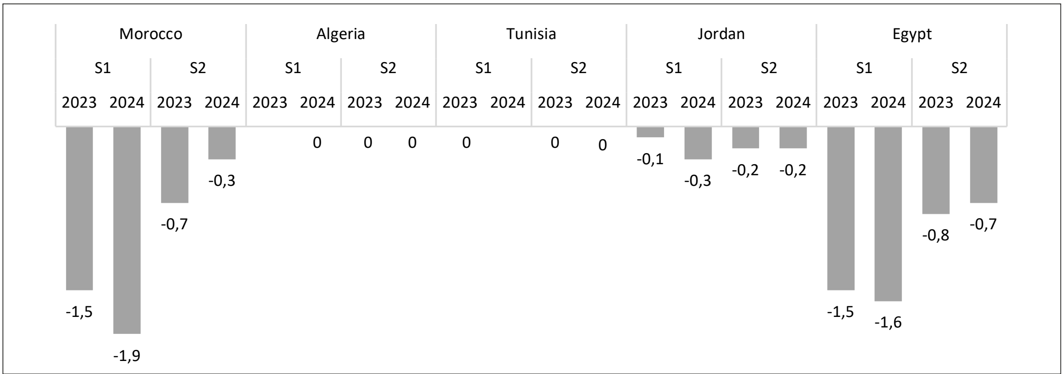
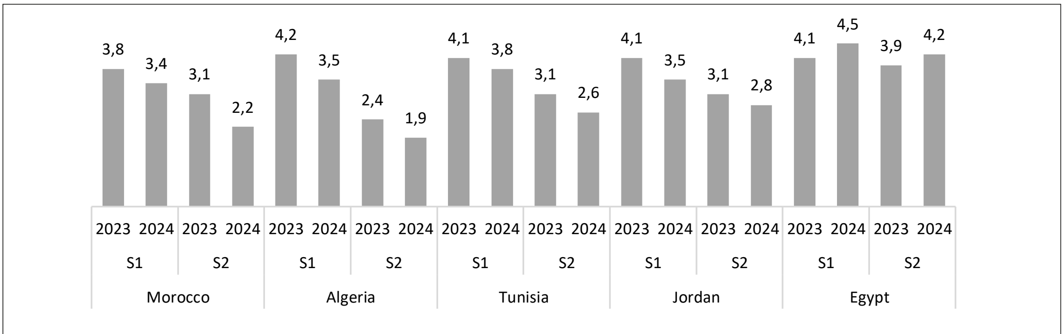


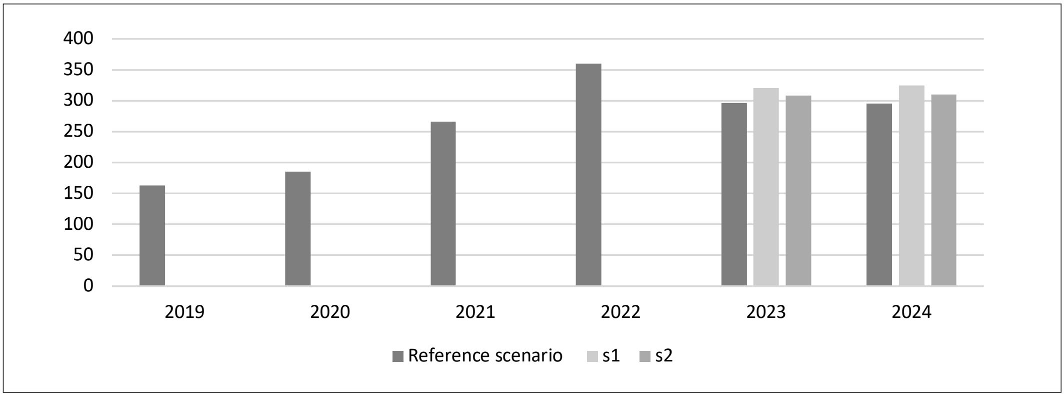
Figure 17 - Impacts on Imports.



the greatest impact in terms of food subsidies which will increase by 8% and 11% in value in USD and by more than 12 and 15% in local currencies to reflect even small devaluations of their national currencies. However, neither consumers nor producers will be directly impacted due to current price-setting policies in the wheat sector in both countries. However, the Tunisian policy of setting production prices for wheat below world levels does little to encourage farmers to extend the production of wheat. For Morocco, Egypt and Jordan, the situation is rather different given the large cuts in food subsidies implemented at different phases of economic reform programs with the IMF. Thus, Morocco should benefit from higher producer prices to increase its production respectively by 5.1% and 5.9% in 2023 and 2024 compared to 4.8% and 5.3% in Egypt and only 1.8% and 2.1% compared to Jordan.

In the second scenario, the increase in the EU's

Figure 18 - Impacts on World Prices of Wheat.



wheat exports is largely due to the surge in imports from Ukraine, which will affect negatively producer prices in all EU's member countries. For the Arab countries, the impacts will once again be negative but at a less pronounced level than the first scenario since the EU will partially finance the drop in world prices through its CAP to protect the income of its farmers due to the competitive wheats imported from Ukraine. Figures 13-17 shows the impacts on the five Arab countries in terms of producer and consumer prices. Production and consumption, and imports.

Finally, work prices of wheat are expected to increase due to the non extending of the black sea deal but in average speaking the expected changes are not too costly for most countries (Figure 16). Despite the armed conflict between Russia and Ukraine and the disturbance of the wheat supply chain, the magnitude of price increase is largely correlated to the available stocks across the word and the policies in managing these stocks. However, the conflict may affect largely the world prices in the future if stock levels decline significantly and world production, outside Ukraine and Russia, decline significantly.

6. Conclusions

The ongoing conflict between Russia and Ukraine has had far-reaching implications across various sectors, mainly agriculture. One of the most affected commodities is wheat, as both countries are significant players in the global wheat market. This paper aims to outline the key impacts of the Russia-Ukraine conflict on the global wheat market with a special focus on a panel of Arab countries.

Russia and Ukraine are major exporters of wheat, together accounting for a substantial portion of global wheat exports. The conflict has disrupted wheat production and exports in Ukraine. This disruption has created uncertainty and volatility in the global wheat supply chain. Due to the conflict, Ukraine's wheat exports have experienced a decline in 2022 but not at a large scale thanks to the black sea agreement on facilitating Ukraine's exports in parallel with sanctions imposed by major developed countries on transport and insurance service providers involved in exporting grains from Russia. This has put pressure on importing nations, leading to volatile prices with several up and down tendencies during the year 2022 and since July 2023. The uncertainty surrounding the conflict and the non-extension of the black sea has contributed to price volatility in the global wheat market. Available data shows that the Russia-Ukraine conflict has had effects on the global wheat market, with disruptions in supply chains, reduced exports from Ukraine and Russia, increased dependency on other exporters, price volatility, and shifting trade patterns. In fact, as wheat exports from Ukraine and Russia dwindle, other major wheat-exporting countries, such as the United States, Canada, and Australia, are being relied upon more heavily to meet global demand. This increased dependency on a smaller pool of exporters has led to heightened competition and price fluctuations in the global wheat market.

As the conflict continues, monitoring the evolving dynamics of the wheat market and its broader economic and geopolitical implications remains crucial for both policymakers and stakeholders in the agricultural industry. The impacts of the two tested alternative scenarios on the non-extension of the black sea deal on Ukraine's grain exports confirms the concerns about global wheat prices. However, despite the redirection of the Ukrainian exports routes simultaneously with a high volatility of monthly and even daily world prices, the average yearly impacts are likely to be short-lived. The resilience of the global wheat market, combined with historical precedents of market adaptation, further supports the fact that the overall effect on global wheat prices will be minimal. As a result, stakeholders in the wheat supply chain can remain relatively optimistic about the stability of the market in the wake of the non extension of the black sea agreement but under some features and assumptions.

All Arab countries are highly sensitive to fluctuations in wheat prices due to their heavy reliance on wheat imports to meet domestic consumption needs. Volatile wheat prices can have profound economic, social, and political consequences in the non rich-oil importing countries through affecting food security, fiscal stability and overall well-being. Sudden spikes in wheat prices can strain government resources in countries that still heavily subsidizing wheat consumptions. However, in the Arab countries where subsidies on wheat are completely or largely removed, vulnerable populations who spend a large portion of their income on basic food items will be the highly affected. For these countries, volatile wheat prices can lead to inflationary pressures, as the cost of bread and other wheat-based products rises. This in turn, can erode purchasing power and reduce disposable income for consumers. In other Arab countries, where wheat and other basic food items still heavily subsidized, governments will face increasing fiscal burdens to maintain these subsidies when global prices surge. This can strain national budgets and divert resources away from other critical areas like healthcare, education, and infrastructure.

The two tested scenarios of the non-renewal of the Black Sea Agreement on the Ukrainian exports of wheat simultaneously with the maintenance of barriers on Russian exports is likely to impact negatively the world wheat prices. However, these effects will depend on three important conditions: the flexibility of EU countries to facilitate the transit of Ukrainian export of wheat, the capacity of the Russian to successfully export its cereals, and the evolution of transport costs for both Russian and Ukrainian wheat exports. The expected increase in global wheat prices is estimated to range between 3 and 4% on average.

For the panel of considered Arab countries, the real challenges are not only those due to the volatility of world prices of wheat, which has been always the case, but on another key factor that needs to be considered in the national reform agendas. The list includes among other, national production, consumption subsidies but also exchange rate regimes and trade finance instruments.

The main lesson learned from this evaluation is that despite the volatility of world wheat prices observed in 2023, which continued in 2024, for multiple reasons other than the shortage on the world market, the average price levels will however be of an additional order which does not exceed 4% on average for the 2023 and 2024. Arab countries are therefore strongly advised to carefully plan the timing of import contracts to avoid price spikes which are directly correlated with certain factors totally exogenous to the grain production sector throughout the world.

Finally, extensive literature showed that the global agricultural landscape is largely shaped by various policies and initiative aimed to support farmers across the world. In the USA and the EU, two major economic players, trade finances and direct extensive farmers' support programs play pivotal roles in influencing wheat prices worldwide. Their effects on world prices of wheat are believed to be much higher than any other disrupt affecting the world wheat market. Trade finances are a critical instrument of trade, providing the necessary funds for exporting countries to facilitate the movement of goods across borders. In the context of the USA and EU, robust trade finance mechanisms have allowed both of them to maintain a steady flow of wheat exports. This consistent supply exerts downward pressure on global wheat prices, benefiting importing nations. However, it can also lead to market saturation, potentially suppressing prices to levels that may not be sustainable for producers in other exporting countries. However, in 2022 and 2023, trade finances have been used largely by major international development banks such as the World Bank and the European Bank for Investment to divert imports of wheat from Russia to other origins mainly EU, USA and Ukraine.

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Assessing environmental and economic dynamics in the EU agri-food sector: The impact of imports through a BVAR analysis

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Abstract

The study investigates the environmental impact of the EU agri-food sector, focusing on emissions per capita and their relationship with economic growth through a Bayesian Vector Autoregression (BVAR) framework. It reveals that greening efforts in the sector have not been matched by sufficient economic growth, challenging the Environmental Kuznets Curve (EKC) hypothesis. Despite progress in sustainable practices, economic expansion has fallen short of offsetting environmental costs, with imports playing a critical role. The Carbon Border Adjustment Mechanism (CBAM) under the EU Green Deal highlights the need to address trade-related emissions. The study calls for future research to develop a comprehensive index incorporating diverse variables to better assess sustainability efforts in the agri-food sector.

Keywords: *Agricultural income, Digitalization, Farmers' education, Green deal, Climate change action.*

1. Introduction

The modern way of life worldwide exerts increasing pressure on natural resources, heightening concerns about their depletion. Rapid population growth and the intensification of industrial and agricultural production amplify these concerns, particularly in light of projections that global food production must double by 2050 to meet the needs of a population expected to reach approximately 9.8 billion by 2050 and 11.2 billion by 2100. These pressures are exacerbated by inefficiencies and losses in the agri-food supply chain, contributing to food

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waste and environmental degradation. According to FAO, one-third of the world's food is lost, impacting 800 million people suffering from hunger, with Europe alone generating 88 million tons of food waste annually. Despite these challenges, the existing literature addressing the intersection of green practices, technological advancements, and economic growth in the agri-food sector remains limited. Current studies largely focus on consumer behavior and demand for environmentally conscious products. Limited work examines the broader systemic changes required to balance economic growth with environmental sustainability, particularly through innovative methodologies or the integration of technology with green practices. Furthermore, the interdependencies between green supply chains, economic efficiency, and sustainability goals are underexplored, especially concerning how policy frameworks like the EU's Common Agricultural Policy (CAP) and global initiatives like the Green Deal address these challenges.

This work aims to bridge this gap by analyzing how green practices, coupled with modern technology, can transform the agri-food sector to achieve eco-efficiency. Eco-efficiency, a term popularized by Schaltegger and Sturm in 1992, links economic and environmental performance by emphasizing sustainable value creation while reducing environmental harm. The study further examines how technological paradigms, such as precision agriculture, can enhance productivity and profitability without exacerbating environmental degradation. Additionally, it evaluates policy impacts, particularly those stemming from the CAP (2023-2027) and Green Deal, on agri-food sector sustainability. The novelty of this study lies in its methodological and analytical approach. Employing advanced techniques such as Bayesian Vector AutoRegression (BVAR), it investigates the economic and environmental interlinkages within the agri-food sector. The study uniquely considers the role of import indices in the context of the Green Deal's Carbon Border Adjustment Mechanism, a measure yet to be widely implemented in the sector. Unlike prior studies focusing narrowly on producer behavior or consumer demand, this research adopts a systemic view, encompassing supply chain coordination, trade liberalization impacts, and policy frameworks to propose actionable pathways for sustainable development in the agri-food sector.

2. Existing Literature

Current agri-food systems face multifaceted challenges that necessitate urgent reform to achieve global food security and sustainability. Food insecurity and malnutrition persist, particularly in low- and middle-income countries (LMICs), where limited resources and inefficient agricultural practices exacerbate systemic vulnerabilities. Compounding these issues are entrenched profit-driven models that resist the adoption of sustainable practices, prioritizing short-term economic gains over long-term ecological stability. Climate change, coupled with economic crises and unpredictable environmental conditions, underscores the critical need for systemic transformation in the agri-food sector (FAO, 2022; IPCC, 2023).

The inefficiencies of current agri-food systems contribute significantly to food waste and environmental degradation. Globally, one-third of food production is lost or wasted, affecting approximately 800 million people who experience hunger. In Europe alone, food waste through the supply system amounts to 88 million tons annually, highlighting the scale of inefficiency (European Commission, 2022). LMICs face additional challenges, including inadequate infrastructure, limited technological access, and economic constraints that hinder their capacity to implement sustainable agricultural practices (Godfray *et al.*, 2021).

Climate change presents a profound threat to global agriculture, with rising temperatures, shifting growing seasons, and extreme weather events disrupting food production patterns. The adverse effects of climate change are particularly pronounced in LMICs, where adaptive capacity is limited (IPCC, 2023). Economic crises and public health emergencies, such as the COVID-19 pandemic, further exacerbate these vulnerabilities, revealing the fragility of global food systems (Benton & Bailey, 2022). Collectively, these challenges necessitate a transformative approach that integrates sustainability into every aspect of the agri-food sector.

International initiatives, such as the Sustainable Development Goals (SDGs), and regional policies, including the European Union's Common Agricultural Policy (CAP) and the Green Deal, provide critical frameworks for addressing these issues. The SDGs, particularly Goals 2 ("Zero Hunger") and 12 ("Responsible Consumption and Production"), advocate for systemic reform to enhance sustainability, equity, and resilience in food systems (UN, 2023). The CAP (2023-2027) allocates significant resources—approximately 23 billion euros—to promote environmentally friendly practices, focusing on climate change mitigation and biodiversity conservation. The Green Deal aims to transition Europe into a sustainable, resilient, and digital economy, with measures such as the Carbon Border Adjustment Mechanism designed to reduce carbon leakage and promote global adoption of sustainable practices (European Commission, 2023).

Technological innovation plays a pivotal role in transforming agri-food systems. Precision agriculture, leveraging data analytics, sensors, and automation, has demonstrated substantial potential to enhance productivity while minimizing environmental impacts (Gebbers & Adamchuk, 2023). Renewable energy integration, intelligent agricultural equipment, and the adoption of bio-pesticides and organic fertilizers represent essential advancements for achieving sustainability (Pretty *et al.*, 2023). Digital technologies, including blockchain, artificial intelligence, and machine learning, further optimize supply chain efficiency, enhance transparency, and reduce waste (Tian, 2023). These technologies collectively facilitate the transition to eco-efficient systems that balance economic growth with environmental preservation.

Abbate *et al.* (2023) emphasize the dual transition towards digitalization and sustainability within the agri-food sector, identifying the critical role of technological advancements in addressing systemic inefficiencies and reducing environmental footprints. Similarly, Belaud *et al.* (2019) highlight the potential of Big Data applications in promoting sustainability through better by-product management in supply chains.

Industry 4.0 technologies, such as automation and IoT, are pivotal in enabling these transformations. Ojo *et al.* (2018) discuss the implications of Industry 4.0 for sustainable food supply chains, stressing its role in improving traceability and reducing food loss. Qian *et al.* (2020) further elaborate on food traceability systems from diverse stakeholder perspectives in the European Union and China, underscoring its global relevance.

Despite the transformative potential of these technologies, their adoption remains uneven across regions, presenting significant challenges. Low-income countries face infrastructural deficits, such as inadequate internet connectivity, lack of electrification, and high costs associated with digital tools, which hinder the deployment of advanced technologies and exacerbate global inequities in agricultural productivity (Lipper *et al.*, 2017). Smallholder farmers, who constitute a significant portion of global agricultural producers, often lack access to financial resources, technical expertise, and training required to adopt digital solutions (Ferroni & Zhou, 2017). Without targeted interventions, these disparities are likely to persist. Additionally, some innovations remain in developmental stages or require customization to address diverse agroecological contexts, which limits their scalability and relevance to different farming systems.

The socio-economic implications of digital transformation in agriculture are profound, offering both opportunities and risks. AI-based demand forecasting optimizes supply chains by aligning production with consumption patterns, thereby reducing food waste and leading to cost savings and environmental benefits (Chen *et al.*, 2020). Digital platforms provide access to new markets, financial services, and supply chain information, empowering farmers and agribusinesses. However, the shift toward technology-intensive farming risks marginalizing smaller farmers who lack the means to compete with larger agribusinesses. This underscores the need for inclusive policies to ensure equitable benefits from these advancements (Pingali *et al.*, 2019).

Sustainability remains a cornerstone of digital transformation in agri-food systems. Innovations offer promising avenues to minimize the environmental footprint of agriculture. Precision irrigation and AI-driven crop monitoring contribute to lower emissions by optimizing resource use. Research indicates potential reductions of up to 20% in greenhouse gas emissions (Rose *et al*., 2021). Blockchain technology supports compliance with environmental standards through transparent monitoring and smart contracts, incentivizing sustainable practices across supply chains (Feng *et al*., 2020).

The convergence of digital transformation and sustainability represents a dynamic and evolving frontier. Realizing the full potential of these innovations will require concerted efforts. Governments and international organizations must develop frameworks that encourage technology adoption while protecting the interests of smallholder farmers. Subsidies, tax incentives, and funding for infrastructure development can address existing gaps. Collaborative efforts among technologists, agronomists, environmental scientists, and policymakers are essential to create integrated solutions. Investments in education and training programs will enable farmers to leverage digital tools effectively, fostering widespread adoption and equitable benefits. By aligning technological advancements with sustainability objectives, the digital transformation of agri-food systems has the potential to revolutionize global agriculture, ensuring food security, economic development, and environmental stewardship.

The concept of eco-efficiency, which emphasizes the integration of economic value creation with environmental preservation, offers a guiding framework for addressing these challenges. Empirical studies demonstrate that eco-efficient practices can significantly reduce greenhouse gas emissions, enhance resource efficiency, and improve economic resilience (Stern, 2023). However, achieving eco-efficiency requires a paradigm shift among industry stakeholders, prioritizing long-term value creation and sustainability over immediate profitability (Schaltegger & Sturm, 2023).

Empirical studies underscore the transformative potential of eco-efficient practices in addressing the interconnected challenges of environmental sustainability and economic viability. Such practices have been shown to significantly reduce greenhouse gas emissions, enhance resource efficiency, and strengthen economic resilience (Stern, 2023). For instance, innovations in waste-to-energy systems, precision manufacturing, and circular economy models contribute to reduced resource depletion and lower environmental footprints. Research highlights that industries adopting these strategies report not only a decrease in operational costs but also an improvement in market competitiveness, as consumers increasingly demand sustainable products and services (Porter & Kramer, 2023).

Achieving eco-efficiency, however, requires more than incremental adjustments; it necessitates a profound paradigm shift among industry stakeholders. Organizations must prioritize long-term value creation, which balances profitability with environmental stewardship and social responsibility. This shift often involves rethinking traditional business models to incorporate principles of sustainability at every stage, from product design to end-of-life management (Schaltegger & Sturm, 2023). Effective adoption of eco-efficiency also depends on fostering a culture of innovation, where sustainability-driven solutions are incentivized and supported.

The role of policy frameworks and regulatory mechanisms is critical in driving this transformation. Governments and international bodies must establish supportive policies, such as tax incentives for green technologies, subsidies for renewable energy adoption, and stringent emissions regulations. These measures create an enabling environment for industries to align their objectives with broader sustainability goals. Public-private partnerships can further amplify these efforts by mobilizing resources and facilitating knowledge sharing, accelerating the transition to eco-efficient practices (Bocken *et al*., 2023; Rochas-Serano *et al*., 2024).

Education and stakeholder engagement are also pivotal. Building awareness among consumers, suppliers, and employees about the benefits of eco-efficiency fosters collective action. Transparent communication and reporting on sustainability performance, guided by frameworks such as the Global Reporting Initiative (GRI) and the Task Force on Climate-related Financial Disclosures (TCFD), ensure accountability and reinforce trust among stakeholders (Elkington, 2023).

For EU recently, the adoption of precision agriculture within the EU has grown significantly, as a means of ecoefficiency aligning closely with the EU's sustainability goals while it was spurred by supportive policies like the Common Agricultural Policy (CAP) and the European Green Deal. CAP has encouraged farmers to implement sustainable and resource-efficient practices, including variable-rate application systems and remote sensing tools. This shift is further supported by the Horizon Europe program, which funds innovative projects such as SmartAgriHubs to develop scalable and adaptive solutions for the region's diverse agricultural needs. As a result, precision agriculture adoption across the EU is projected to reach over 25% of farms by 2025, with a compound annual growth rate exceeding 12% (European Commission, 2023).

The precise application of water, fertilizers, and pesticides minimizes waste and runoff, preserving soil health and promoting biodiversity. A recent study by the Joint Research Centre (JRC) found that precision irrigation reduced water use by 20% without compromising crop yields. Furthermore, practices such as controlled traffic farming and optimized nutrient management contribute to a reduction in greenhouse gas emissions, supporting the European Green Deal's objective of achieving climate neutrality by 2050.

In addition, the EU's dependency on agricultural imports by improving domestic production efficiency and supply chain resilience. Enhanced yield predictability and optimized resource management make the EU more self-sufficient in critical commodities, such as grains, oilseeds, and proteins. In a global context characterized by geopolitical uncertainties and trade disruptions, these advancements bolster the EU's food security. Additionally, blockchain technology integrated into precision farming enhances supply chain transparency, enabling traceability and reinforcing consumer trust in sustainably produced EU goods. This combination of innovation and sustainability has strengthened the EU's position as a global leader in exporting high-quality agricultural products.

While existing literature has explored various aspects of sustainability in the agri-food sector, significant gaps remain. Research on the interdependencies between green practices, technological innovation, and economic growth is limited, particularly regarding their combined impact on global trade and supply chain dynamics. Additionally, the role of policy frameworks, such as the Green Deal and CAP, in shaping international trade and sustainability outcomes requires further exploration (Vermeir & Verbeke, 2023).

This study addresses these gaps by employing advanced quantitative methodologies to analyze the economic and environmental interlinkages within the agri-food sector. By examining the role of policy measures, such as the Carbon Border Adjustment Mechanism and import indices, this research provides a comprehensive understanding of how international trade and sustainability goals intersect. The findings aim to inform policymakers and industry stakeholders on actionable pathways to achieve a resilient, sustainable agri-food sector capable of meeting future demands while safeguarding environmental integrity.

The paper is organized as follows: section 2 describes the data and the methodology employed, section 3 highlights the results of the methodology, section 4 discusses the results and the lastly section 5 presents the conclusions and policy implications, specifying the scientific value, practicality, as well as the limitations of the study.

3. Data - Methodology

3.1. *Data*

The objective of this manuscript is to achieve its aim by developing a model that integrates key factors, including carbon emissions generated by the agri-food sector, value added per capita, and imports within the EU or the specific sector under review. In alignment with the greening objectives mandated by the Common Agricultural Policy (CAP), this study aims to model and estimate the relationship between the sector's greening initiatives and its economic growth. The research builds a theoretical foundation by exploring eco-efficiency, which focuses on aligning economic output with reduced environmental impact, and the Environmental Kuznets Curve (EKC), which suggests that environmental degradation initially rises with economic growth but eventually declines at higher income levels (Panayotou, 1993; Schaltegger & Sturm, 1990).

While eco-efficiency emphasizes optimizing the ratio of economic output to environmental impact through deliberate actions and technological innovation, the EKC examines the trajectory of environmental degradation across stages of economic development. Together, these frameworks offer complementary perspectives on the dynamics of environmental and economic sustainability. Eco-efficiency underscores the necessity of proactive measures to reduce environmental impact, challenging the optimistic assumption inherent in the EKC that economic growth alone will eventually lead to reduced environmental degradation. By prioritizing intentional strategies and innovations, eco-efficiency addresses the urgent need for sustainable practices in ways that the EKC framework, reliant on natural economic trajectories, does not fully encompass.

To comprehensively capture the interlinkages among these variables, the study formulates the following empirical function:

$$f(EMIti, VAAi, Impp) \tag{1}$$

where EMIti, denotes the emissions per capita
GDP generated by agriculture per capita
Imp denotes import index

The dataset employed in this study encompasses annual data spanning the period 1990-2020, with a specific focus on the European Union (EU) treated as a single entity. The data were obtained from FAOSTAT and include three key variables: emissions per capita in the agri-food sector (utilized as a proxy to evaluate the greening of the agri-food sector), the GDP per capita share attributed to agriculture (indicative of economic growth within the EU), and an index reflecting changes in the cost, insurance, and freight (c.i.f.) values of imports, all denominated in US dollars. These variables were chosen to provide a comprehensive understanding of the interplay between sustainability, economic performance, and trade in the EU's agri-food systems.

The selection of emissions per capita as a proxy for the greening of agri-food systems is grounded in the pivotal role of reducing greenhouse gas (GHG) emissions in achieving sustainability. The transition to more sustainable practices within agri-food systems is intrinsically linked to mitigating climate change and environmental degradation. Despite policy efforts and technological advancements, the pace of this transition has lagged behind expectations, particularly in comparison to the broader decline in total EU GHG emissions. This discrepancy underscores the persistent challenges in decarbonizing the agri-food sector.

FAOSTAT data reveal the substantial environmental footprint of agri-food systems, extending beyond agricultural production to include processing, transportation, and consumption stages. These downstream activities significantly contribute to the sector's overall emissions, highlighting the need for a systems-wide approach to sustainability. Globally, agri-food systems account for approximately 30% of total GHG emissions, illustrating their critical role in addressing climate goals. Within the EU, this sector remains a focal point for achieving targets under the European Green Deal, which aims for climate neutrality by 2050.

The inclusion of GDP per capita share generated by agriculture provides insight into the economic contributions of the sector, reflecting its role in supporting livelihoods and driving regional development. Simultaneously, the index tracking changes in c.i.f. values of imports captures the trade dimension of the EU's agri-food systems, offering a perspective on how external dependencies and global market dynamics intersect with sustainability objectives.

By integrating these variables, the dataset serves as a robust foundation for analyzing the complex interactions among environmental performance, economic resilience, and trade patterns in the EU's agri-food systems over three decades. This longitudinal perspective enables the identification of trends, challenges, and opportunities critical for steering the sector toward a more sustainable and equitable future.

Analyzing the emissions trajectory and the proportional contribution of agri-food systems reveals a consistent downward trend since 2000, though progress has been constrained by continued fossil fuel combustion for energy. Simultaneously, non-food-related emissions within the sector have surged, increasing by 50% since 2000. In absolute terms, per capita emissions attributed to agri-food systems decreased from 2.4 t CO_2eq/cap in 2000 to 2.0 t CO_2eq/cap by 2020, reflecting a modest but meaningful reduction over two decades.

In the European Union (EU), agri-food systems remain a significant contributor to the region's carbon footprint, accounting for approximately 33% of total EU emissions in 2020. These emissions encompass a wide range of activities that extend beyond agricultural production. Specifically, they include emissions generated within the farm gate, those arising from land-use changes such as deforestation and soil degradation, and emissions linked to pre- and post-production processes, including food processing, transportation, packaging, and waste management.

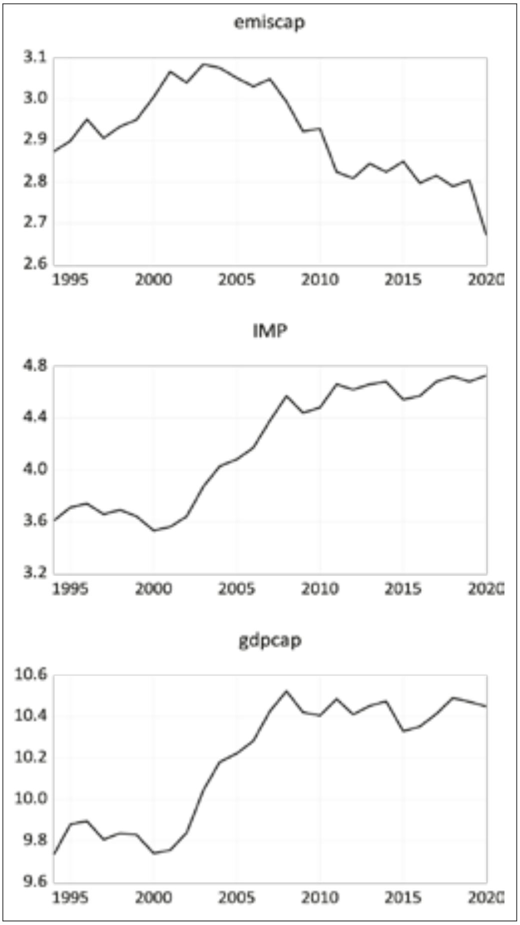
The comprehensive calculations that inform these figures integrate data from multiple reputable sources. Key datasets include the United Nations Statistical Division (UNSD), the International Energy Agency (IEA), and third-party analytical tools. Additionally, the PRIMAP-hist dataset v2.4 has been instrumental in synthesizing historical emissions data and providing a consistent basis for comparison across time and regions (UNSD, 2022; IEA, 2021; Gütschow *et al.*, 2021). These datasets collectively enable a granular examination of emissions drivers and trends, helping policymakers and stakeholders identify critical intervention points.

Despite the observed reductions in per capita emissions, the agri-food sector's emissions trajectory highlights ongoing challenges. The increasing prevalence of energy-intensive agricultural practices and the expansion of non-food agricultural activities—such as biofuel production—have offset some of the gains achieved through efficiency improvements and sustainable practices. Furthermore, emissions from land-use change remain a persistent issue, particularly in regions where agricultural expansion continues to drive deforestation and habitat loss.

The evolution of the data employed and for the reference period 1990-2020 are illustrated in the next Figure 1.

As illustrated in the figure the GDP share generated by agriculture is stationary and slightly

Figure 1 - Evolution of the model variables employed (1990-2020).



increasing for a time period of five years a sharp increase in 2000 and after that an unstable movement implicitly oscillations are evident without a concise growth.

On the other the emissions are increasing with a declining trend in the first two decades though then the slope of the curve is changing and has become sharply decreasing within the last decade.

Regarding the role of imports, the evolution pattern is similar to that of the gdp share though the import index is increasing even in the year 2018 though this is not the case for the GDP per capita that is decreasing.

Evidently and based on the above figure the emissions intensity is slowing down without a clear positive income effect to be validated and also with a significant value of the import index rejecting the hypothesis of ecoefficiency. The graphical illustration shows that exploring the interlinkages of the particular variables could highlight the path for ecoefficiency in EU agri-food sector.

3.2. *Methodology*

The BVAR methodology is the framework employed for the above-mentioned variables (Sarantis & Stewart, 1995; Yan et al., 2022; Tsioptsia *et al*., 2022; Narayan & Popp, 2013). The Bayesian Vector Autoregression (BVAR) model builds upon the standard Vector Autoregression (VAR) framework by incorporating Bayesian statistical principles, offering several advantages and operating under key assumptions. BVAR assumes that the variables in the system are interdependent, meaning they influence each other dynamically over time. For example, in this study, emissions, economic growth, and trade are presumed to have mutual, time-dependent relationships. Additionally, the model typically assumes stationarity, which means that the time-series data have statistical properties, such as mean and variance, that do not change over time. If the data are not stationary, transformations like differencing are applied to stabilize these properties. Another foundational assumption of BVAR is the incorporation of prior information, which is drawn from theoretical knowledge, past studies, or expert opinion. This prior knowledge guides the estimation process and is particularly valuable when the available data is limited or noisy. Furthermore, BVAR operates within a probabilistic framework, explicitly accounting for uncertainty in its predictions and parameter estimates. Instead of providing single-point forecasts, it offers probabilistic intervals, such as confidence or credible intervals, to represent the range of likely outcomes (Koop, 2003).

BVAR holds several advantages over traditional VAR models. First, it addresses the issue of overfitting, a common problem in VAR models that arises due to the need to estimate a large number of parameters, especially when the dataset is small. By incorporating Bayesian priors, BVAR constrains parameter estimates and reduces the risk of overfitting, resulting in more robust model performance. Second, BVAR often yields improved forecasting accuracy because it integrates prior knowledge with observed data, making it particularly effective when dealing with short or noisy datasets. Third, the Bayesian approach adeptly handles multicollinearity, a situation where predictor variables are highly correlated, which can destabilize traditional VAR models. Finally, BVAR offers greater interpretability and flexibility, allowing researchers to transparently quantify uncertainty in predictions and adjust the model to incorporate different prior beliefs or assumptions (Karlsson, 2013).

To make this more accessible to non-specialists, BVAR can be thought of as combining the strengths of observed data and expert knowledge. If traditional VAR is like navigating without a map and relying solely on what you observe, BVAR is akin to navigating with both a map and the terrain in view. The "map" (prior knowledge) complements the "terrain" (data), particularly when the data is sparse or noisy, resulting in a more informed and reliable decision-making process.

Prior to the analysis implementation, we conducted a Break Unit root test in order to test the rank of variables' integration (Bloor & Matheson, 2011). The next step in our analysis involved the implementation of the BVAR methodology in order to detect the interlinkages among green practices implementation and economic growth in the agri-food sector as well as to unveil the role of imports (Nyangchak, 2022). The Bayesian VAR is employed as it is considered a more efficient methodology compared to the classical VAR model. The mathematical form of a BVAR model does not differ though the parameters' estimation and interpretation is different. More specifically, the BVAR models incorporate prior information about model parameters allowing the authors to get more reliable results given that this process provides stability in the parameter estimation. The prior specification employed in our BVAR model is Minnesota while the posteriors' estimation is based on Maximum likelihood function (Sarantis & Stewart, 1995; Yan *et al*., 2022; Tsioptsia *et al*., 2022; Narayan & Popp, 2013; Nyangchak, 2022).

A tractable posterior density function is generated being similar to the one of the prior with

Minnesota algorithm for the parameter under review (Yan *et al.*, 2022). The Bayesian Vector Autoregression (BVAR) model with the Minnesota prior addresses the overfitting and instability challenges of traditional VAR models, especially when data is limited. Introduced by Litterman (1986), the Minnesota prior shrinks coefficients toward a random walk baseline, where a variable's own lags are assumed to have more influence than lags of other variables. This shrinkage reduces overparameterization and improves forecast accuracy.

The Minnesota prior's key feature is its hyperparameter, controlling the degree of shrinkage. Tighter priors pull coefficients closer to zero, favoring simplicity unless the data strongly supports otherwise. Its computational efficiency stems from assuming a diagonal prior covariance matrix, avoiding complex methods like MCMC.

Studies, including Litterman (1986) and Banbura *et al.* (2010), highlight its effectiveness in forecasting macroeconomic variables and handling high-dimensional VARs. This makes the Minnesota prior a powerful tool for balancing flexibility and parsimony in systems like environmental and economic modeling.

Thus, the hyperparameter value is equal to the value of the prior μ while the covariance prior is non zero. Furthermore, the matrix of error terms is Null, under the condition that the variance-covariance matrix is diagonal. The next step in our BVAR analysis involves the specification of the target parameter, having incorporated a set of hyperparameters variables (Yan *et al.*, 2022; Tsioptsia *et al.*, 2022; Narayan & Popp, 2013). The small value of $\lambda 1$, is attributed to the fact that the prior information is more efficient than the sample information. The parameter, $\lambda 2$ is the regulator of the lag significance of the other variables and the parameter $\lambda 3$ reflects the impact of the exogenous variable on the endogenous variable. Finally, $\lambda 4$ unveils the data scale and variability differences, with the lag loss to be either linear when $\lambda 4=1$, harmonic or geometric in case $\lambda 4>0$ (Yan *et al.*, 2022; Tsioptsia *et al.*, 2022; Narayan & Popp, 2013).

The last step in our analysis involves the impulse response function estimation (IRF) for each variable as well as the Forecast Variance Decomposition Analysis (FEVD). Impulse Response Analysis is a fundamental tool in econometrics and time series analysis for examining the dynamic interactions among variables in multivariate models. It evaluates how a shock to one variable propagates through the system over time, affecting other variables. The methodology has evolved significantly, with notable contributions by Koop *et al.* (1996) and Pesaran and Shin (1998), who expanded its applicability to nonlinear and linear multivariate frameworks, respectively.

Koop *et al.* (1996) introduced Impulse Response Analysis for nonlinear multivariate models, addressing limitations of traditional linear approaches. Their work provided a robust framework for analyzing systems where relationships between variables may vary depending on the state of the system. For instance, in macroeconomic models, the effects of policy changes might differ during periods of economic expansion versus recession. Their methodology captures these complexities, making it particularly useful for analyzing real-world economic dynamics where nonlinearity is prevalent.

Pesaran and Shin (1998) advanced the field by developing Generalized Impulse Response Analysis (GIRA) within linear multivariate models. Unlike traditional approaches that rely on orthogonalization via Cholesky decomposition—which imposes a specific ordering of variables—GIRA provides a flexible and ordering-invariant methodology. This innovation is particularly valuable in settings where the causal ordering of variables is ambiguous or controversial, such as in macroeconomic studies examining interactions between monetary policy, inflation, and output. By allowing shocks to be modeled in a less restrictive manner, GIRA facilitates more realistic and interpretable analyses. The practical implications of these developments are extensive. In policy analysis, IRF enables researchers and policymakers to simulate the effects of interventions, such as fiscal stimulus or monetary tightening, on key economic indicators over time. In financial markets, it aids in understanding how shocks to interest rates or stock prices influence interconnected markets. Moreover, the adaptability of these methodologies to both linear and nonlinear systems has broadened their applicability across diverse fields, including environmental modeling, health economics, and industrial organization (Koop *et al*., 1996; Pesaran *et al*., 1998).

In a similar vein, variance decomposition or in other words 'forecast error variance decomposition is a specific tool that may interpret adequately and in a narrow way the relations between variables described by the model estimated. This methodology will amplify the impulse Response analysis since further quantify the contribution rates of all variables to the impact on the dependent variable (Ivanov & Kilian, 2005; Brahmasrene *et al*., 2014; Jakada *et al*., 2022; Lanne & Nyberg, 2016; Pesaran & Shin, 1998).

The model evaluation was based on the forecast accuracy performance for the classic VAR and BVAR specifications respectively with the assistance of the following indices namely the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE). Their calculation was based on the following formula (Pesaran & Shin, 1998):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n}} \tag{17}$$

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n}|y_i-\bar{y}|}{n} \tag{18}$$

The forecast accuracy measures were selected on the basis of sensitivity extending to the deviations from the true values.

4. Results

The first step in our analysis, namely the break unit root test employed has provided the following results as synopsized in Table 1.

Based on the aforementioned findings for the EU all the respective variables are found to be I(1) with the years 1999 and 2002 respectively to be identified as structural breaks. The Kyoto protocol (1996-1999 signing period) as well as the different financial crises may well interpret the breakpoints identified.

The Impulse Response analysis was also employed in order to detect and quantify the interlinkages among the variables employed. Based on our findings the response of agricultural income due to an innovation to the emissions is decreasing with a steady declining rate the slope becomes steeper after the five years while a balance and a constant route is evident within the last few years. In addition, the response of emissions to an innovation in agricultural income is initially increasing at an increasing rate while this change in the mid-term since the curvature of the response changes and from curved becomes cave. The results are provided in Figure 2.

The figures constructed were based on the Bayesian methodology Gibbs sampling while 1000 iterations were implemented to acquire the results (Solazzo & Pierangeli, 2016; Kasztelan *et al*., 2019; Kovalenko *et al*., 2021).

Based on the Impulse Response Analysis (as illustrated in Figure 3), an innovation in emissions seem to steadily decrease the emissions rate for a 20-period studied. On the other hand, an innovation in imports and GDP share seems to in total decrease the emission for the time period studied though in a limited way with imports to be more effective than GDP share. Regarding the response of imports on the innovation of the emissions is initially increasing with a decreasing rate and then decreasing after a 1-period time.

The GDP increases with a declining trend for a period of twenty years while the emissions increase with a declining trend in the first decade though then the slope of the curve is changing and becomes increasing.

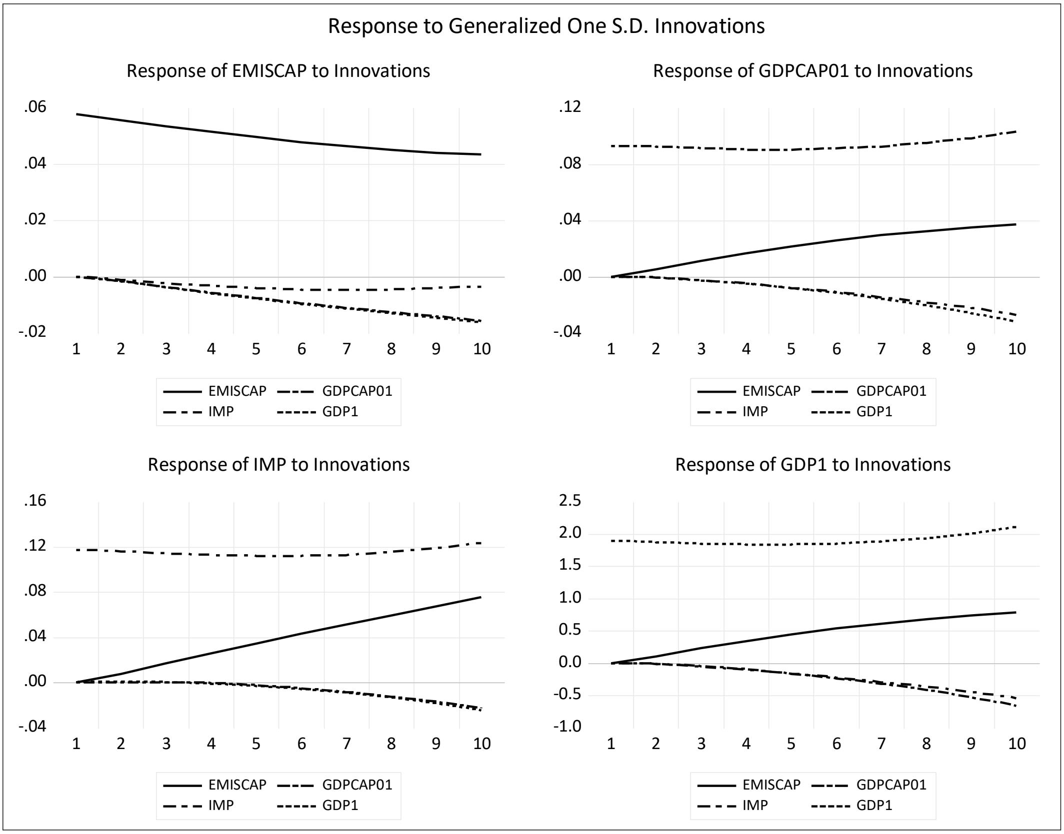
Based on the above results it becomes evident that natural processes, such as livestock manure, enteric fermentation, and land use, contribute

Table 1 - ADF break unit root results.

Variables	*ADF Break Unit Root*	*Break date*
CEM	-3.33 (0.778)	1999
ΔCEM	-5.50*** (0.000)	2001
GDP	-3.81 (0.48)	2002
ΔGDP	-4.82*** (0.0)	2003
IMP	-4.35* (0.06)	2002
Δ IMP	-5.03*** (000)	2000

**** reject of unit root test for 1% level of significance with critical values -4.94, -4.44, -4.19 for 1,5 and 1% level of significance CEM denotes carbon emission per capita for agrifood system for EU, GDP denoted GDP per capita, IMP denotes the import index for EU and ΔCEM ΔGDP, ΔIMP denotes the first differences of the variables respectively*

Figure 2 - Impulse – response analysis of the model variables (10-period).

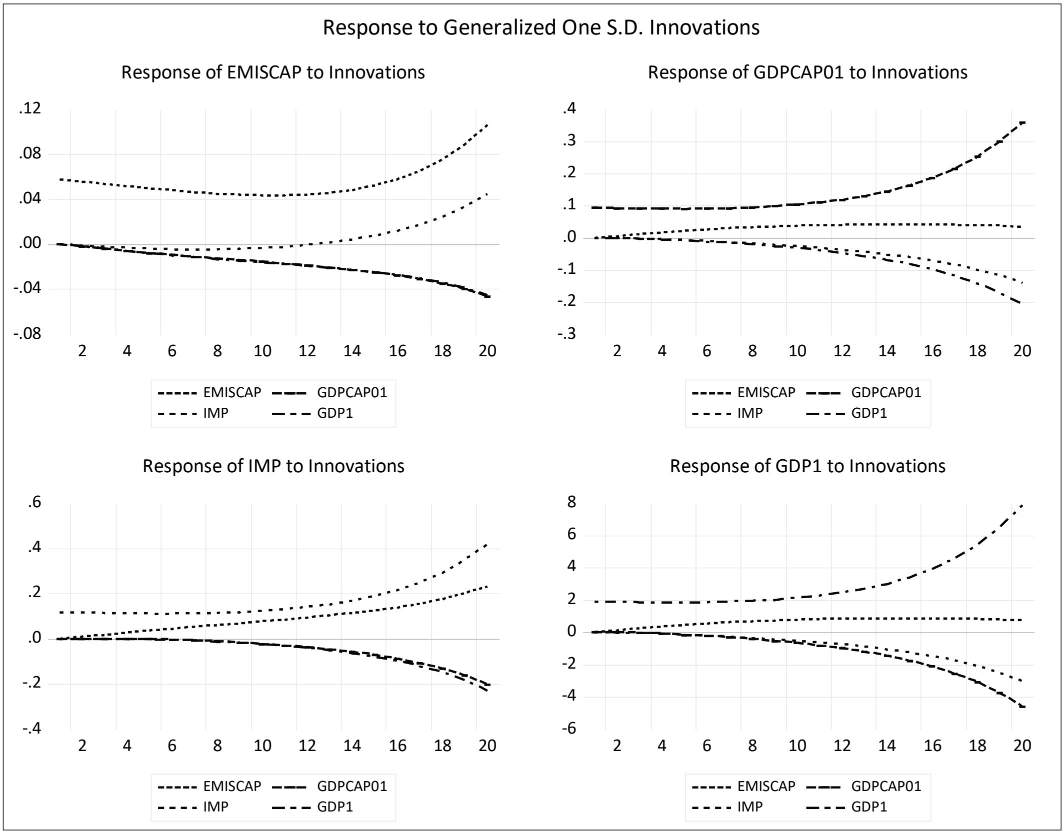


greatly to methane emissions, making agriculture a major part of the agri-food sector hard to abate. What is more, fertilizers hurt the climate through the release of nitrous oxide. There are however solutions to reduce emissions from agrifood systems, such as the introduction of environmentally friendly and efficiency improvement through automation. The particular solutions could enable a reduction in the emission intensity (that is the level of GHGs released per kg of product) of specific food commodities. EU production of livestock products, have decreased in emission intensity in recent decades. According to calculations by the European Topic Centre on Climate Change Mitigation, policies and measures currently in place are expected to cause only a 1.5 % reduction in the agricultural sector's emissions between now and 2040. This result implies that more steps should be taken to enhance the efficient limitation of environmental degradation. On the other hand, the response of imports on innovation of emissions tends to increase linearly the index related to the imports while innovations on GDP decrease the imports throughout the period studied. Last but not least the response of GDP share per capita generated by agriculture in case of innovations in emissions leads to an increase in GDP with a declining rate while stability becomes evident within ten years.

This means that the greening of the agrifood sector cannot provide a steadily increasing growth and therefore more steps need to be taken in order ecoefficiency to become an achievable objective in the EU.

When the impulse response analysis involves twenty periods an innovation in imports causes an increase in emissions while an innovation in GDP share generated by agriculture causes a decrease in emissions. The significant change becomes more evident after the 12th period. What

Figure 3 - Impulse – response analysis of the model variables (20-period).



is more the innovation in emissions has a slight impact on GDP and the same variable is slightly decreasing for innovation in imports.

The forecast error variance decomposition analysis reveals more insightful results after 20 periods compared to 10. Specifically, for emissions volatility, only 10% is attributable to GDP volatility, while 4.2% can be explained by volatility in imports. These findings highlight the limited interconnectivity between the variables analyzed, suggesting that the relationships among emissions, GDP, and imports are not strongly interdependent within the framework employed. For a 10-period reference, the explanatory power of the variables is even more constrained, providing less meaningful insights into their dynamics. Importantly, these patterns remain consistent across other variables in the study, indicating that the observed trends are robust but that further investigation is needed to identify additional factors influencing emissions and their interrelationship with economic growth and trade. This underscores the need to explore alternative causal pathways to effectively prioritize environmental sustainability in the agri-food sector while mitigating potential adverse income effects. Another notable observation concerns the limited impact of imports on both income and environmental outcomes. This suggests that while trade policies and imports play a role, their influence is not as pronounced as other factors. These findings highlight the need for a multifaceted approach to address environmental issues in the agri-food sector, emphasizing strategies that integrate sustainability goals without compromising economic resilience. Further research should aim to uncover additional drivers and refine the policy framework to enhance the sector's capacity for sustainable growth.

Another step involves Sims-ZHA analysis

Table 2 - Generalized FEVD Analysis (Lanne and Nyberg, 2016).

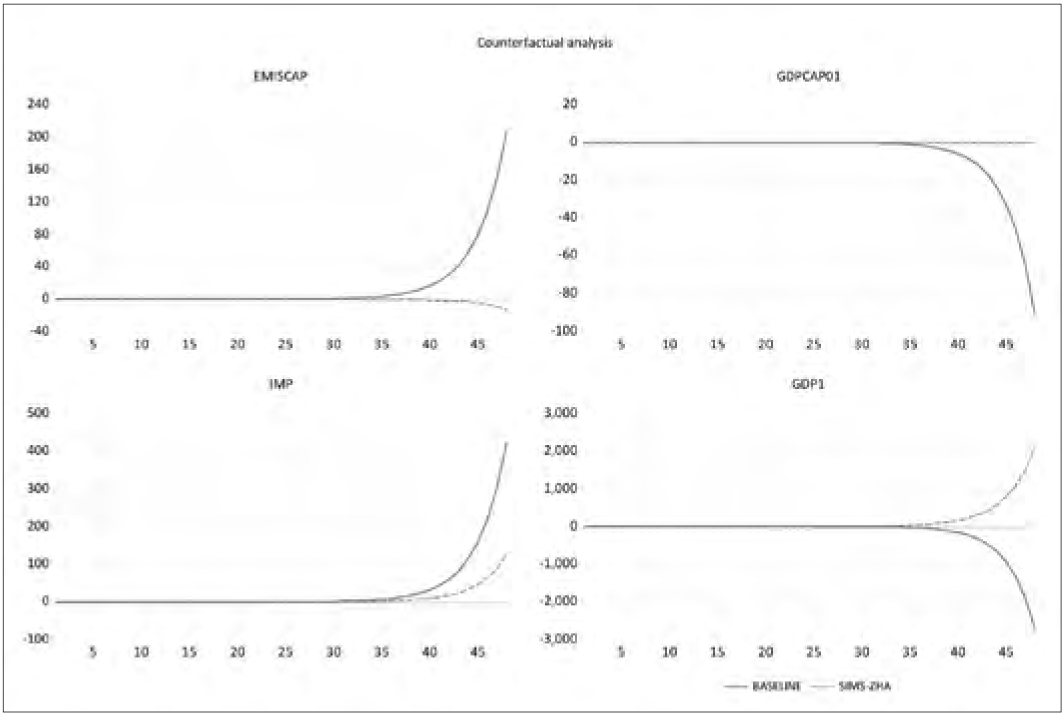
Variance decomposition of EMISCAP				
	EMISCAP	GDPcap^2	GDPCAP	IMP
1	100.0000	0.000000	0.000000	0.000000
2	99.89138	0.044249	0.039874	0.024496
3	99.54465	0.190690	0.176762	0.087895
4	98.97621	0.435923	0.410263	0.177600
5	98.21348	0.772122	0.734676	0.279725
6	97.28471	1.190762	1.142862	0.381661
7	96.21727	1.683418	1.627002	0.472306
8	95.03644	2.242190	2.178953	0.542421
9	93.76440	2.859942	2.790446	0.585209
10	92.41928	3.530395	3.453117	0.597210
11	91.01400	4.248007	4.158355	0.579633
12	89.55533	5.007555	4.896887	0.540223
13	88.04295	5.803291	5.657999	0.495764
14	86.46903	6.627492	6.428330	0.475143
15	84.81894	7.468288	7.190241	0.522534
16	83.07365	8.306819	7.920033	0.699503
17	81.21525	9.114289	8.586779	1.083678
18	79.23585	9.850376	9.153248	1.760528
19	77.14858	10.46541	9.580789	2.805225
20	74.99640	10.90863	9.839142	4.255823

Variance decomposition of GDPCAP01				
	EMISCAP	GDP1	GDPCAP01	IMP
1	0.000000	0.000000	100.0000	0.000000
2	0.154966	0.004576	99.83738	0.003075
3	0.595799	0.038281	99.33147	0.034455
4	1.265362	0.121255	98.50143	0.111957
5	2.091764	0.274871	97.38292	0.250447
6	3.001357	0.520989	96.01495	0.462707
7	3.923122	0.881538	94.43593	0.759410
8	4.791541	1.377864	92.68173	1.148867
9	5.548732	2.029866	90.78475	1.636656
10	6.146201	2.854688	88.77408	2.225034
11	6.546498	3.864792	86.67666	2.912050
12	6.724978	5.065280	84.51935	3.690395
13	6.671703	6.450544	82.33160	4.546150
14	6.393230	8.000724	80.14825	5.457796
15	5.913635	9.678952	78.01132	6.396094
16	5.273828	11.43080	75.96988	7.325488
17	4.528206	13.18741	74.07690	8.207485
18	3.738328	14.87284	72.38304	9.005789
19	2.964463	16.41468	70.92878	9.692072
20	2.257090	17.75502	69.73728	10.25061

Variance decomposition of GDP1				
	EMISCAP	GDP1	GDPCAP01	IMP
1	0.000000	100.0000	0.000000	0.000000
2	0.153244	99.84115	0.002055	0.003556
3	0.590360	99.35067	0.023941	0.035028
4	1.257957	98.54816	0.082998	0.110881
5	2.088408	97.46837	0.198456	0.244765
6	3.012193	96.14865	0.391098	0.448059
7	3.961928	94.62539	0.682906	0.729778
8	4.874824	92.93233	1.096516	1.096329
9	5.694467	91.09992	1.654450	1.551167
10	6.372263	89.15551	2.377947	2.094284
11	6.868835	87.12451	3.285175	2.721483
12	7.155578	85.03225	4.388698	3.423478
13	7.216458	82.90641	5.692171	4.184963
14	7.049918	80.77950	7.186608	4.983977
15	6.670398	78.69060	8.846973	5.792024
16	6.108683	76.68547	10.63035	6.575495
17	5.410130	74.81400	12.47718	7.298694
18	4.630177	73.12509	14.31644	7.928298
19	3.827417	71.65961	16.07464	8.438342
20	3.055633	70.44365	17.68643	8.814286

Variance decomposition of IMP				
	EMISCAP	GDP1	GDPCAP01	IMP
1	0.000000	0.000000	0.000000	100.0000
2	0.205939	0.000505	0.001105	99.79245
3	0.836548	0.000367	0.001147	99.16194
4	1.874776	0.003656	0.001256	98.12031
5	3.277107	0.019844	0.007223	96.69583
6	4.983297	0.063195	0.028978	94.92453
7	6.921659	0.151912	0.079737	92.84669
8	9.013041	0.307231	0.175216	90.50451
9	11.17411	0.552406	0.332871	87.94061
10	13.32003	0.911452	0.571057	85.19746
11	15.36674	1.407475	0.908003	82.31779
12	17.23319	2.060448	1.360452	79.34591
13	18.84414	2.884310	1.941873	76.32968
14	20.13379	3.883472	2.660217	73.32252
15	21.05074	5.049137	3.515411	70.38471
16	21.56393	6.356276	4.497078	67.58271
17	21.66845	7.762474	5.583229	64.98584
18	21.38949	9.209932	6.740825	62.65976
19	20.78219	10.63122	7.928754	60.65784
20	19.92612	11.95813	9.103022	59.01272

Figure 4 - Sims-Zhu policy analysis results of the model variables.



through which we try to conclude how policy measures adoption on climate change would affect the behavior of the other variables. Based on policy measures taken for climate change mitigation we may conclude that the emissions become limited, the GDP share generated by agriculture is stabilized while the imports are increasing with a less steep upward trend. This result is significant since the proper climate change mitigation measures may lead to ecoefficiency. All the results are illustrated in next Figure 4.

The last but not least step in our analysis involves a forecast analysis (Figure 5). More specifically, the averages, and the actual values over the periods, provides a quick visual comparison of the model variables but in the present work we illustrate the result for the emissions generated by the agri-food sector in EU.

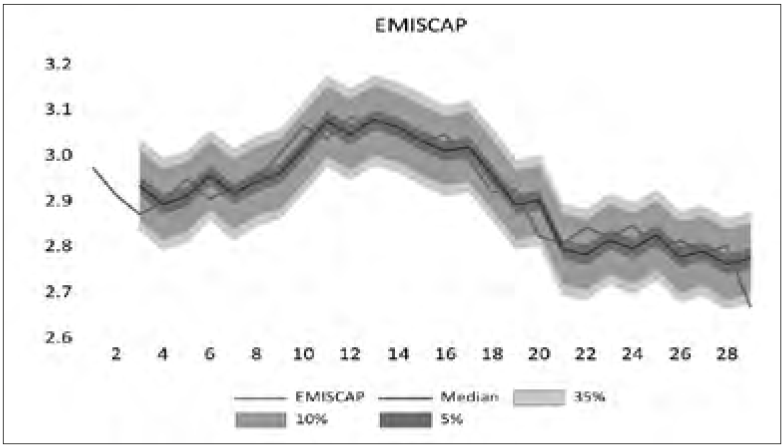


Figure 5 - Real and average values of the emissions generated by the estimated model.

Table 3 - Forecast Model's evaluation statistic results for all the variables.

Variable	*RMSE*	*MAE*	*MAPE*	*Theil*
EMISCAP	0.042251	0.034328	1.190075	0.007236
GDP1	1.530497	1.228946	1.187841	0.007351
GDPCAP01	0.075314	0.060488	0.594720	0.003694
IMP	0.093340	0.072838	1.766562	0.011057

The emission estimated based on the model lies within a band of 5% oscillation indicating that the model employed is accurate. The above findings are further validated with the indices provided in the table below including RMSE, MAE, MAPE and Theil validate model accuracy indices.

The following section provides a detailed interpretation of the derived results and outlines their policy implications. This analysis aims to translate the findings into actionable insights, offering a foundation for informed decision-making to address key challenges and opportunities identified in the study.

5. Discussion - Conclusions

Green and sustainable practices in the agri-food sector have become increasingly prevalent in modern societies, particularly within the European Union (EU). This trend is strongly supported by policies such as the Farm-to-Fork Strategy, which aligns with the Sustainable Development Goals (SDGs) to provide nutritious and affordable food for a growing global population. The EU's strategy specifically aims to create fair, healthy, and environmentally-friendly food systems. The EU's strategy aims to establish fair, healthy, and environmentally sustainable food systems. A cornerstone of this approach is the European Green Deal, which sets an ambitious goal of making Europe carbon neutral. This wide-ranging policy framework encompasses all sectors of the economy, with agriculture playing a pivotal role. Within the Green Deal, the Farm-to-Fork Strategy focuses on building sustainable food systems that protect human health, support society, and safeguard the environment. One of the Green Deal's key targets is to reduce greenhouse gas (GHG) emissions by 50–55% compared to 1990 levels, underscoring the EU's strong commitment to combating climate change and advancing sustainability throughout the agri-food sector (Belaud *et al*., 2019; Annosi *et al*., 2021; Notenbaert *et al*., 2020; Fanzo *et al*., 2020; FAOSTAT, 2018; Andrieu & Kebede, 2020). To achieve the ambitious targets set by the European Green Deal and the Farm-to-Fork Strategy, several key actions are essential within the agri-food sector. To minimize environmental and health impacts, a 50% reduction in the use and risk of chemical pesticides is essential. This requires promoting alternative pest management strategies and encouraging the adoption of safer, more sustainable solutions.

Simultaneously, nutrient losses—especially nitrogen and phosphorus—must be reduced by at least 50% to prevent water pollution and eutrophication, without compromising soil fertility. Achieving this will depend on improved nutrient management and the implementation of precision agriculture techniques.

Fertilizer use should also be decreased by at least 20% to curb environmental damage, particularly greenhouse gas emissions and soil degradation. This calls for optimized fertilization practices, including the use of organic and enhanced-efficiency fertilizers.

Furthermore, the sale of antimicrobials for farm animals and aquaculture must be halved to combat the escalating threat of antimicrobial resistance. This underscores the need for better animal husbandry, stronger biosecurity measures, and the development of effective alternative treatments. Expanding the area of farmland under organic farming to 25% by 2030 is crucial for promoting biodiversity, improving soil health, and reducing chemical inputs, thereby contributing to more sustainable food systems. These measures are vital for meeting the EU's sustainability goals, ensuring that the agri-food sector contributes to a healthier environment, more resilient food systems, and a reduced overall carbon footprint for agriculture (van Bers *et al*., 2019; Boix-Fayos & de Vente, 2023).

This study employs the Bayesian Vector Autoregression (BVAR) methodology to investigate the interlinkages between emissions per capita from the agri-food sector, used as a proxy for greening, and GDP per capita. The findings reveal that current efforts to achieve greening in the agri-food sector remain largely ineffective. While carbon emissions have decreased, these reductions are not accompanied by proportional improvements in economic efficiency. The EU's "Farm-to-Fork" strategy, a pivotal component of the Sustainable Development Goals (SDGs), seeks to deliver nutritious and affordable food while fostering sustainability. However, the progress achieved thus far is insufficient to meet these ambitious objectives.

The limitations of current greening efforts highlight the urgent need for policies that leverage the potential of digitalization and innovation. Precision mechanization, automation, and advanced data-driven decision-making systems present promising solutions to the sector's environmental and operational challenges. Real-time data acquisition and instantaneous information sharing can significantly enhance traceability, promoting greater sustainability and transparency across the agri-food supply chain. This is particularly important as consumers are increasingly concerned about the structure and integrity of these supply chains, especially in response to recurring food safety scandals and emerging risks over recent decades.

Advancing sustainable food systems requires a multifaceted approach that integrates technological innovation, consumer education, and coordinated efforts across stakeholders. Policymakers must create enabling environments for the adoption of digital tools, such as precision agriculture and blockchain, to improve resource efficiency and supply chain transparency. Education and training initiatives organized by cooperatives, research institutions, policymakers, and academics are critical for equipping farmers and other decision-makers with the knowledge needed to implement sustainable agricultural practices. Regulatory frameworks should also be strengthened to ensure that greening efforts align with broader economic and environmental goals.

The analysis of the impact of imports on carbon emissions reveals only a limited effect. Using Impulse Response Function (IRF) and Forecast Error Variance Decomposition (FEVD) methods, the study finds that although an increase in imports slightly elevates carbon emissions and reduces the agri-food sector's contribution to GDP, these effects are relatively minor. The FEVD analysis indicates that only 8.8% of emissions volatility can be attributed to changes in imports. This limited influence can be attributed, in part, to initiatives like the Carbon Border Adjustment Mechanism (CBAM), introduced under the EU Green Deal. CBAM imposes a carbon price on imports from countries with less stringent environmental standards, thereby reducing carbon leakage. However, additional trade restrictions within the agri-food sector could reduce imports further, potentially leading to significant economic repercussions. These include decreased production, reduced exports, higher food prices, increased food insecurity, lower farmer incomes, and potential GDP declines.

The results of this study align with and expand upon findings from prior research. Abbate *et al*. (2023) emphasize the importance of digital and sustainable transitions in the agri-food sector [Technological Forecasting and Social Change]. Similarly, Dora *et al*. (2021) propose a system-wide interdisciplinary framework for mitigating food loss and waste in supply chains [Industrial Marketing Management]. Belaud *et al*. (2019) explore the role of big data in sustainability management for agri-food supply chains [Computers in Industry]. Furthermore, Annosi *et al*. (2021) discuss the integration of digitalization to prevent food waste [Industrial Marketing Management].

In alignment with Ojo *et al*. (2018), this study underscores the transformative potential of Industry 4.0 technologies in achieving sustainable food supply chains. Additionally, Fanzo *et al*. (2020) highlight the role of decision-support tools, such as the Food Systems Dashboard, in informing better policy decisions.

The limited impact of imports on emissions is consistent with the findings of FAOSTAT (2018) regarding trade and sustainable agri-food systems. Furthermore, the challenges posed by policy lock-ins, as noted by Kuokkanen *et al*. (2017), and the need for innovative pathways, as discussed by Boix-Fayos and de Vente (2023), underscore the urgency of adopting transformative measures within the EU's Green Deal framework.

Based on the above, this study highlights the urgent need for transformative policies and innovative solutions to align the greening of the agri-food sector with economic growth. Policymakers must balance trade policies with sustainability goals, ensuring that mechanisms such as CBAM are complemented by investments in technology, education, and infrastructure. Only through coordinated actions and robust policy frameworks can the EU achieve the dual objectives of environmental sustainability and economic resilience within the agri-food sector.

The Farm-to-Fork strategy, a cornerstone of the Sustainable Development Goals (SDGs), aims to provide nutritious and affordable food on a global scale while promoting sustainability. Implemented across various stages of the EU agri-food industry, the strategy has made some progress, but achieving eco-efficiency in this sector demands additional efforts. This study's examination of the long-term interlinkages within the sector highlights the evolving nature of these relationships as the Green Deal advances and new data becomes available.

A key limitation of this study is its reliance on time series analysis that treats the EU as a single entity. While this approach provides valuable insights, effective policy solutions may require a more granular analysis at the member state level. Future research could address this by employing panel data analysis techniques, such as Dynamic Ordinary Least Squares (DOLS) or Fully Modified OLS, to gain a deeper understanding of the economic and environmental efficiency of policy measures. These methods could help identify the specific steps necessary to improve outcomes and ensure alignment with the targets set by the SDGs and the Green Deal.

Additionally, the role of imports in shaping the agri-food sector warrants further investigation. As the Green Deal progresses and import restrictions evolve, it will be crucial to understand their broader implications. In particular, future research should focus on the origins of imports from countries that do not adhere to emerging environmental standards. Expanding the dataset to include more detailed observations would allow researchers to capture the dynamics of the global agri-food market as it adapts to these changes.

This ongoing analysis will be instrumental in refining policies and practices to address the dual challenges of climate change and the transition to sustainable food systems. A more nuanced understanding of these interdependencies is critical for the formulation of integrated strategies that align environmental sustainability with economic resilience. Such an approach is instrumental in advancing the aims of the Farm-to-Fork Strategy, the Sustainable Development Goals (SDGs), and the European Green Deal.

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Distribution strategies in the value chain of Spanish virgin olive oils

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Abstract

In Spain, the world's leading olive oil producing country, the existing literature points to a malfunctioning of the value chain, since it hardly generates any profits and some links often incur losses. The aim of this research paper is to analyze the value chain of virgin olive oils, establishing the relationship between the prices of virgin olive oils at origin and the retail prices paid by the end consumer. The methodology used is the analysis of the value chain using quantitative research through descriptive statistics and the process of quantitative data collection under observation together with other statistical methods. The data on retail prices have been obtained from the published information of the commercial operations of the retailers themselves, while the data on prices at origin come from the price statistics elaborated by national (Spain) and international (European Commission) organizations. The conclusions point out that the retail price of virgin olive oils by the distributors does not reflect the real production cost of the product, as it is more a concept of customer attraction strategy on the part of the distributors.

Keywords: *Virgin olive oils, Value chain, Costs & Margins, Retail prices, Agri-food chain.*

1. Introduction

In Spain, as a leader in olive oil production, a recurring issue is the study of the costs of olive growing and olive oil production, due to the importance of the sector as a socioeconomic driver. In this regard, the Spanish Ministry of Agriculture, Fisheries and Food of Spain (MAPA, 2023a) describes the olive oil sub-sector as a fundamental pillar of the Spanish agri-food system. Moreover, its world leadership is justified by Spanish production, which, according to the International Olive Council (COI, 2024), represents 70% of European Union (EU) production and 45% of world production.

As for the studies that address the value chain, most of them analyze the production costs of olives on the one hand and olive oil on the other (Diputación Provincial de Jaén, 2007; Consejería de Agricultura, Pesca y Desarrollo Rural, 2015) and, although from the beginning, most of them have focused on the first link in the chain, in recent years, published studies have focused

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on all links in the chain (Observatorio de la Cadena Alimentaria, 2021a, 2021b and 2023).

The theoretical basis for determining the retail price of a product is established on the basis of the production costs and the margins of each of the participants in the value chain. In the case of virgin olive oils this situation is not the case due to factors intrinsic to the subsector itself: a) the concentration of demanders; b) the atomization of supply; c) the introduction of the Common Agricultural Policy (CAP) concept; d) the concept of a basic product in the shopping cart with no capacity for differentiation and e) the specific characteristics of a perishable product (Gómez-Limón and Parras, 2017).

Recently, the Ministry of Agriculture, Fisheries and Food of Spain has analyzed the costs of the different links of the value chain in three consecutive campaigns (2018/2019, 2019/2020 and 2020/2021) (Observatorio de la Cadena Alimentaria, 2021a, 2021b and 2023). In the final report there is a comparison of the costs of these three campaigns where it is shown that the agricultural sector is the weakest link, accumulating losses or meager profits when there are any. However, losses have never been found in the packing sector and, in the last campaign analyzed, distribution appears with a negative average margin (Observatorio de la Cadena Alimentaria, 2023). These studies suggest that the prices of virgin olive oils paid by the end consumer do not obey the standard construction of costs and margins that would have to be added by each operator.

Therefore, the study question is whether there is a standard construction of the price of virgin olive oils along the different links of the chain or whether the retail price paid by end consumers is due to other commercial strategies of the operators in the chain.

In order to answer the question, the study objective will focus on analyzing whether the difference in the comparison of retail prices with olive mills' prices at origin is a constant over time and, in any case, sufficient to include packers' and distributors' costs and margins. Otherwise, there must be other factors involved in the strategy of price construction.

The relevance of this study lies mainly in the methodology that it actually applies. In order to analyze the value chain and in the lack of studies on historical series of retail prices of a kilogram of virgin or extra virgin olive oil packaged in large self-service grocery stores: Supermarkets and Hypermarkets (LSSGS), it has been necessary to develop the following paper, which serves as the basis for the subsequent analysis.

From 2016 to 2022, the retail price (RP) of virgin olive oils were taken every twenty-five days from the commercial publications issued by the main Spanish retailers or distributors ('Alcampo', 'Aldi', 'Carrefour', 'Hipercor', 'Lidl', and 'Makro'). An extensive database has been compiled with them, differentiating between Polyethylene Terephthalate (PET) or glass, packaging capacity, organic or conventional and private label or brand name. All this has given us the opportunity to construct real retail prices throughout this period, which have been homogenized at prices per kilogram in order to be able to compare them with the prices at origin (OP) of the official statistics. The previous studies of the value chain have been carried out through surveys on costs and margins, but not on retail prices.

The sequence of the study is developed as follows. After this introduction, where the research area has been delimited, the need for the study justified and the objectives and methodology established, the following section is devoted to the theoretical review. While the third section focuses on developing the research method used, the fourth section analyzes the results obtained. The conclusions point to the fact that the selling price of virgin olive oils does not reflect the real production cost of the product, but rather responds more to a concept of customer attraction strategy on the part of the retailer.

2. Theoretical Framework

According to Porter (1985 and 1990), competitiveness is based on greater economic efficiency or greater differentiation in the execution of these activities within the value chain. The main utility of the value chain lies in improving competitiveness and reducing costs, thus increasing value creation (Robben and Quatrebarbes, 2018).

Normann and Ramírez (1993) argue that the analysis should not focus on the fixed activities of a value chain, but on the value creation system as a whole, where mutual value arises from cooperative interactions. Along these lines, Miller and Jones (2010) pointed out that a chain is only as strong as its weakest link.

For value chains to be sustainable, several conditions apply: a chain needs to generate sufficient value for each link; consumer requirements must be accurately communicated throughout the chain; and the value that a product represents for the consumer must be disclosed and communicated to the target market (McEachern and Schröder, 2004).

With the advent of the Agricultural Value Chain concept, we move away from a segmented form of linkage system in which many separate links operate in isolation rather than synchronizing with each other (McCullough *et al*., 2008). Fries (2007) postulates that value chain analysis is essential for understanding markets, their relationships, the participation of different actors and the critical constraints that limit the growth of agricultural production and, consequently, competitiveness.

Value chains work best when their actors cooperate to produce higher quality products and generate more income for all links (Norton, 2014). In agriculture, chains can be considered as a set of processes and flows from 'farm/field to fork' (Miller and Da Silva, 2007). Conducting a value chain analysis requires a thorough assessment of the changes between actors in a chain, what holds them together, what information is shared and how the relationship between actors is evolving (Sanogo, 2010). In this sense, authors such as Fetoui *et al*. (2024) analyze the olive oil value chain from the relationships between its main operators to bring about effective participation and better performance and resilience in the subsector.

In relation to the sector under study, virgin olive oils, i.e. those corresponding to the virgin and extra virgin categories, are part of the end consumer's shopping cart as a basic product and as part of the Mediterranean culture with a limited capacity for differentiation, which could be categorized as a commodity.

We must make an important mention to the types of price transmission in the vertical value chain in the agricultural, fishing and livestock sectors, which have been extensively studied by Goodwin & Holt (1999), Meyer & Cramon-Taubadel (2004), Arida *et al*. (2023) and Kidane (2025), all of them describing an asymmetry in the transmission, when changes in prices are not transmitted in an equal way. The main factors affecting this transmission process are logistics costs, price reconfiguration, dominant players in the market, demand elasticity and public policies (CAP, tariffs, etc.). And the models that explain it are basically Error Correction Models (ECM), Vector Autoregressive Models (VAR) and Cointegration Models.

We are now focusing on the study of the value chain and the obtaining of prices and margins in the Spanish olive oil sub-sector. The Spanish market is characterized by its asymmetry, with many suppliers (producers) and few demanders (distributors or retailers) (Consejo Económico y Social de la Provincia de Jaén, 2011). According to Parras (2011), the concentration process in the distribution sector, together with the dominance of private labels, has led to an asymmetry in the bargaining power between large-scale distribution and the olive oil agri-food industries. Therefore, it follows a priori that prices are determined by large-scale distribution, which, together with annual production volumes, tend to set the market trend.

The question that arises is whether the price paid by the end consumer for a liter of bottled virgin or extra virgin olive oil has any relationship with the prices at origin or is configured independently (Gutiérrez-Salcedo *et al.*, 2015) thus pointing to a commercial strategy led by the distribution.

All published studies point out that the price paid by the end consumer for a liter of bottled virgin or extra virgin olive oil does not correspond to the real price of costs and margins of the different links involved in the value chain. The Spanish Ministry of Agriculture indicates that it is a paradox that one of the most important subsectors in Spanish agriculture is scarcely profitable, for the grower, and not very transparent in the construction of its prices (MAPA, 2023a).

The research carried out on the olive oil value chain is largely focused on the primary sector, with the aim of characterizing it and establishing a cost structure and production margins according to the types of olive groves (Consejería de Agricultura y Pesca, 2010; Torres Velasco *et al*., 2011; Consejo Económico y Social de la Provincia de Jaén, 2011; Consejería de Agricultura, Pesca y Desarrollo Rural, 2015; COI, 2015; Penco, 2020). These studies point out that only intensive and super-intensive plantations (they represent a minimum percentage) are profitable, so producers need the Common Agricultural Policy (CAP) subsidies to survive.

Other studies have focused on the entire value chain of the olive oil subsector (Observatorio de la Cadena Alimentaria, 2021a, 2021b and 2023). These were the first to attempt to establish, empirically, the lack of a causal relationship between the retail price of virgin oils and their costs at each stage of production. They conclude that on a regular basis the grower together with the distributors (although the latter for different reasons) obtain negative operating margins in most scenarios. These same studies indicate that packers always obtain meager but positive operating margins (Observatorio de la Cadena Alimentaria, 2021a, 2021b and 2023). Other studies are along the same lines (Diputación Provincial de Jaén, 2007; Consejería de Agricultura y Pesca, 2010; MARM, 2010 and Observatorio de Precios de los Alimentos, 2012).

Focusing on the analysis of the negative operating margins of growers and distributors, the difference between the two lies in the fact that the first ones do not have the capacity to negotiate their sales prices because they are highly atomized and do not have the strength to negotiate, while the second ones do because they are highly concentrated in large purchasing platforms. A different thing is that, even if distributors can configure the selling price of olive oils to generate positive margins, they do not do so in order to attract consumers to their stores and thus be able to sell other products with a higher profit margin, using olive oil as a "lure product" (Consejo Económico y Social de la Provincia de Jaén, 2011; Olimerca, 2017).

García (2006) states that large-scale distribution sets very tight prices for a series of mass-purchased products with little degree of differentiation in order to extend the image of a "cheap" establishment. These products are called "hook products" or "traffic generators". In the most extreme case of this commercial strategy, there are "sales at a loss".

Theoretically, the concept of market asymmetry is explained by the fact that in all of Spain and also in Andalusia, distribution is dominated by only five large groups: 'Mercadona', 'Carrefour', 'Auchan', 'Dia' and 'Eroski'. (Savills Aguirre Newman, 2020), while they produce olive oil in Andalusia and, where appropriate, pack a total of 802 olive mills (Junta de Andalucía, 2022), while in Spain as a whole there are 1,837 for the 2021/2022 campaign (MAPA, 2023c). Clearly, the existing imbalance between suppliers and demanders or purchasing groups, which also hold more than 80% of the market share of the olive oil subsector, can be observed (MAPA, 2022).

Something unusual happens in the olive oil subsector: retail prices are significantly lower than they should be due to the regular increase in the value chain (Observatorio de Precios de los Alimentos, 2010). This is expressed by Gutiérrez Salcedo *et al*. (2015), when they state that the commercial policies of the last links of the extra virgin olive oil chain are focused on maintaining low and stable prices for end consumers, being fundamental for their competitive strategy. Thus, prices seem to be determined more by price variation at destination than by price changes at origin. This would not be a problem if it were not for the fact that setting these prices excessively low would imply dumping (Olimerca, 2016a and 2016b).

What Gutiérrez Salcedo *et al*. (2015) point out about the keeping of stable prices by distribution corresponds to what is expressed by Vavra and Goodwin (2005), who wonder about the speed and extent to which changes in agricultural prices are transmitted to the retail trade and vice versa. They argue that it is important to distinguish between the analysis of the evolution of margins over time and the transmission of prices along the agrifood chain. Conclusions on pass-through drawn from the evolution of trade margins over time that do not incorporate other information, such as the evolution of other input costs, may be erroneous. They limit themselves to analyzing vertical price transmission, adjustment to price shocks along the chain being an important feature of market functioning. They claim that, due to imperfect price transmission (caused by market power and oligopolistic behavior), a price reduction is only slowly, and possibly not fully, transmitted through the supply chain. In contrast, it is believed that price increases are transmitted more quickly to the end consumer.

The objective of Vavra and Goodwin (2005) is to analyze the mechanisms of asymmetric price transmission and to explore the evidence that empirically measures such transmission. They focus on vertical price transmission and discuss possible types of adjustments to a price shock.

In this way, and following the theory of the value chain and the vertical diagram, the Spanish olive oil subsector is composed of the following links with their corresponding production costs (C) and margins (M):

1. Farmers/Producers: their production costs vary according to the type of cultivation, but based on studies it comprises a range of between 2.07 and 3.56 €/kg (IOC, 2015). In Spain they represent 73.07% of the costs of the value chain (Observatorio de la Cadena Alimentaria. (2021b), data very similar to that expressed by Sarni *et al*. (2024) where he states these are in Tunisia close to 70%. The costs are those of olive growing: fertilization, irrigation, pruning, purchase and application of phytosanitary products, harvesting of the crop, etc.
2. Olive mill: costs related to the reception and classification of olives, milling, filtering and bulk storage.
3. Packers: their costs are directly related to the packaging of different packs and volumes: filling, capping, labeling, packaging, warehouse management and logistics.
4. Distributors: this link is mainly made up of large purchasing centers that monopolize most of the distribution market. The associated costs are logistics, warehouse management and point-of-sale management.

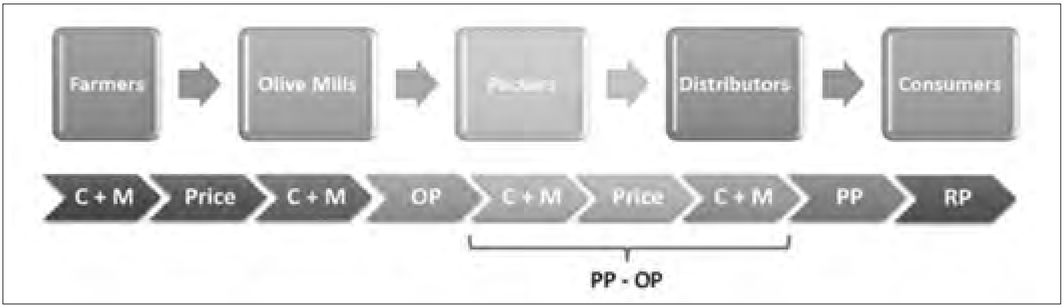
The diagram of the value chain shows the costs and margins for each link in the chain, as well as the transfer prices from one link to another, the object of this study is the prices at origin (OP) and sales prices (PP). The former correspond to the prices that the olive mills set for the product and that the packers pay, while the latter correspond to the prices that the distributors set for the final product, that is, for the virgin olive oils packaged and ready for sale to the end consumers. In the middle is the price that packers set for the packaged product and that distributors pay to subsequently put it on sale in their stores.

In view of the above arguments and following the contributions of the aforementioned authors, our hypothesis is based on the fact that the retail prices of virgin olive oils, as a standard and basic good in the shopping cart in Spain, are determined following the commercial strategy of the distribution and do not follow the standard vertical construction of the value chain, having an asymmetric behavior in the transmission of prices.

3. Methodology

The study is based on the systematic analysis over 6 campaigns of a unique compilation of retail prices (RP) of virgin olive oils from all the commercial operations of different distribution companies in Spain. The importance of this study lies in the fact that there is no record of a

Figure 1 - Value chain of virgin olive oils.



Source: own elaboration.

similar database, neither for the volume of data in the sample, nor for its qualitative part, nor for its time frame.

From October 2016 to April 2022, every 25 days, the different commercial operations of 6 main Supermarket and Hypermarket Food Chains (LSSGS) established in Spain: 'Alcampo', 'Aldi', 'Carrefour', 'Hipercor', 'Lidl' and 'Makro', were obtained and analyzed through their publications (commercial brochures).

All virgin olive oils were considered in the sample because they account for more than 80% of total olive oil production (MAPA, 2022) and because their production process is basically the same and, therefore, their costs are nearly identical.

All the commercial brochures published within the time frame of the study were used as a database for calculating the product price ex VAT (PP) based on the published retail price (RP). Thus, the following variables were extracted from each of the brochures: name of the distributor, category (Supermarket and Hypermarket Food Chains -LSSGS- and Hard Discount -HD-), year and month of publication, type of packaging (PET or glass), packaging formats (from 250 ml to 5 liters), brands or private label, category of olive oil, the retail price per liter, and whether the price was on sale or not (discount amount).

Once the database was set, the retail price (RP) per liter was established. The tax effect of VAT (10%) was also discounted, obtaining the product price without taxes (ex VAT Price). This last final product price (PP) without taxes, which was in euros per liter, was converted to euros per kilograms of olive oil in order to be able to carry out the subsequent homogeneous analysis with the prices at origin (OP), which are always shown in €/kg olive oil.

The different dates of the commercial brochures of all the distribution companies subject to the study were homogenized, establishing the criterion of incorporating them into the month in which they had been active for the most days. In this way, the product price (PP) could be monthly to be compared later with the prices at origin (OP), whose published statistics are based on months.

After these 6 years of work, a total of 394 price references in their different formats, brands and categories were counted. A true picture of the price evolution of olive oils sold by the large-scale distributors was thus obtained.

Once the PP database in current euros has been prepared, in order to establish an approximation of the margins and costs of large-scale distribution and packers, we focused on obtaining the price at origin database, also in current euros.

The prices at origin (OP) are those selling prices of virgin olive oils from private and cooperative olive mills without packaging, i.e., in bulk. They were obtained from the databases published by the European Commission (Agriculture and Rural Development, 2022) and the Price and Market Observatory of the Regional Government of Andalusia (Observatorio de Precios y Mercados, 2022 and 2023).

In total, 3,757 weekly price data were extracted from the European Commission and 134 monthly price data extracted from the source of the Price and Market Observatory of the Andalusian Regional Government. Both databases were merged on a monthly basis. Subsequently, with the two previous monthly databases, a new common and homogeneous statistical sample was established with average prices by campaigns in €/kg olive oil, using the arithmetic mean criterion. For the present analysis it has not been substantial to work with weighted averages, since the study is based on prices and not on prices linked to production or sales.

Following the criteria established in all the literature published to date, the study established the period of each campaign from October to September of the following year. For this reason, both the product price samples (PP) and the prices at origin (OP) have been worked with aggregated data by season, since the monthly figures of these samples allows such data processing.

This study is based on the use of the methodology for the construction of prices, costs and margins of the value chain. Descriptive statistics was used for all the data analysis, due to its ease of aggregation and visualization of the data of this type of sample, allowing its exposition in an understandable way, in addition to other statistical techniques.

To further deepen the study, a simulation was carried out using data from the Agrifood Chain Observatory (Observatorio de la Cadena Alimentaria, 2021a, 2021b and 2023), comparing them with our figures to establish whether there is any evidence to support our working hypothesis. In this way, under the assumption that packers allocate 100% of their costs and margins, we have analyzed whether the difference between PPs and OPs for the comparative campaigns allows distribution to incorporate their costs and margins, partially or totally. Therefore, this simulation is a practical advance in the use of the price difference as a tool for investigating the use of the value chain by distribution or packers as a tool for price construction.

4. Results

After homogenizing and analyzing the two databases obtained for virgin oils (PP and OP), the following results were obtained:

1. The average difference obtained between the PP and the OP is 0.95 €/kg. This figure should be sufficient for both, packers and distributors to be able to allocate all their costs and obtain profitability.
2. There is an asymmetric price transmission between the OPs and the PPs. Compared to OP increases of 90.31%, the PP only increased by 41.56%.
3. For OP > 3.50 €/kg the differences between PP and OP show a result of 0.63 €/kg (the lowest obtained), while for OP < 1.99 €/kg such price differences show a result of 1.12 €/kg (the highest obtained).
4. The highest campaign in terms of production obtained the highest difference between PP and OP: 1.18 €/kg and the lowest production campaign obtained the second highest price difference with an amount of 1.10 €/kg.

The first result achieved from the analysis indicates that, during the period studied (2016/2017 to 2021/2022 campaigns), no PP was below the OP. The above means that there is a positive difference, greater than zero, which, in theory, allows the links of packers and distributors to allocate costs and profit margins.

The average difference obtain between PP and OP was 0.95 €/kg. This suggests that both, packers and distributors, have on average that amount to cover costs and profit margins. However, further studies would have to quantify that this difference is sufficient to be able to affirm it empirically.

The second result shows that there is a direct, although not proportional, relationship between OP and PP. As both prices increase, the differences also increase, although to a lesser extent. Thus, a 90.31% increase in OP (from 1.96 €/kg to 3.73 €/kg) meant only a 41.56% increase in PP (from 3.08 €/kg to 4.36 €/kg).

Table 1 - Average prices at origin and product prices per campaigns for virgin olive oils.

Campaigns	*OP Average (€/kg)*	*PP Average (€/kg)*	*Average Difference (€/kg)*
2016/2017	3.68	4.29	0.61
2017/2018	3.11	4.06	0.95
2018/2019	2.43	3.61	1.18
2019/2020	2.01	3.11	1.10
2020/2021	2.85	3.74	0.89
2021/2022	3.26	4.20	0.94
Average	*2.89*	*3.84*	*0.95*

Source: own elaboration.

Table 2 - Evolution of the average price difference by campaign of virgin olive oils by price range at origin.

OP Range (€/kg)	*OP Average (€/kg)*	*PP Average (€/kg)*	*Average Difference (€/kg)*	*Amplitude Average Difference (%)*
OP > 3.50	3.73	4.36	0.63	16.89
3.49 > OP >3.00	3.23	4.21	0.98	30.34
2.99 > OP > 2.50	2.66	3.74	1.08	40.60
2.49 > OP > 2.00	2.19	3.21	1.02	46.57
1.99 > OP	1.96	3.08	1.12	57.14
Amplitude ranges (%)	*90.31*	*41.56*		

Source: own elaboration.

This result confirms that there is an asymmetric price transmission mechanism. Thus, it could be demonstrated that the distribution uses the PP of virgin olive oils in a strategic way by keeping them stable to attract consumers, resisting to pass on 100% of the increase in OPs.

As a third result, for OP above 3.50 €/kg, the average OP was 3.73 €/kg and the PP was 4.36 €/kg, which implied a difference between both prices of 0.63 €/kg, the lowest obtained. While for OPs below 1.99 €/kg the difference was 1.12 €/kg, the highest obtained. The direct consequence of these results is that in high OP environment, packers and distributors are less able to allocate their costs and margins. However, in OP campaigns below 1.99 €/kg this difference was 1.12 €/kg, so there is a greater capacity to allocate costs and obtain higher profitability.

This third result confirms the asymmetric transmission and points to reinforce the hypothesis of retailer control of PPs as a commercial strategy, keeping them in a price range that they consider optimal to provoke purchase by consumers regardless of their profitability.

The fourth result was obtained by cross-referencing the differences in PP and OP with the olive oil productions of the campaigns under study. Thus, the largest average difference (1.18 €/kg) is seen in the campaign with the highest olive oil production (2018/2019). In that campaign, there was a drop in the OPs more than in the PPs, which were adjusted more smoothly. In this case, it took advantage of the low-price environment to improve profit margins, but we do not know if this higher profit margin was for the packers or distributors. However, harvests with very similar productions (2016/2017 - 2017/2018 - 2020/2021) obtained very different price differences (0.61 €/kg - 0.95 €/kg - 0.89 €/kg), implying a poor relationship between productions and PPs.

This last result shows that the distribution with very unequal production campaigns managed to maintain the price differences above 1.10 €/kg by controlling the PP and putting pressure on the OP. Once again, the asymmetry hypothesis is reinforced, where the weakest links, producers and olive mills (included in the OP) have no buying power vis-à-vis the large purchasing centers (PP), which are highly concentrated.

5. Discussion

The above results show that the construction of the PP by the distribution does not follow a standard and logical construction of the value chain, that there is an asymmetric price transmission between the link of the OP and the link of the PP, that the higher the OP the smaller the difference between the PP and the OP, so that the repercussion of the costs and margins for the packaging and distribution or marketing links is more and more insufficient. There is an intention to keep the PP in a price range fixed by the distribution in order to use virgin olive oils as a commercial strategy.

Given this demonstration, packers and distributors would not have sufficient margin to be able

Table 3 - Average of the difference between prices at origin and product prices by campaigns and production of virgin olive oils over total production of olive oils.

Campaigns	*Production (kg)*	*Total Production (kg)*	*Average Difference (€/kg)*
2016/2017	1,081,135	1,281,738	0.61
2017/2018	1,060,141	1,238,629	0.95
2018/2019	1,453,320	1,790,309	1.18
2019/2020	904,889	1,129,233	1.10
2020/2021	1,090,984	1,356,411	0.89
2021/2022	1,125,308	1,389,566	0.94
Average	*1,119,296*	*1,364,314*	*0.95*

Source: own elaboration based on MAPA data.

Table 4 - Correlation index between production of virgin olive oils per campaigns and OP & PP.

Campaigns	*Production (kg)*	*OP Average (€/kg)*	*PP Average (€/kg)*	*Correlation Index (kg vs OP)*	*Correlation Index (kg vs PP)*
2016/2017	1,081,135	3.68	4.29		
2017/2018	1,060,141	3.11	4.06		
2018/2019	1,453,320	2.43	3.61		
2019/2020	904,889	2.01	3.11		
2020/2021	1,090,984	2.85	3.74		
2021/2022	1,125,308	3.26	4.20		
Average	*1,119,296*	*2.89*	*3.84*	*-0.0088*	*0.1365*

Source: own elaboration.

to allocate their costs and profit margins in a high OP environment. But it seems difficult to think that packers would not be able to allocate their costs and profits, since they are part of an intermediate link without any kind of requirement or reason not to do so, since they work on demand. However, this is not the case with distributors, who have to dispose of the packaged olive oils purchased and who need to have a basic product to attract consumers while maintaining control over prices.

The data presented so far support the hypothesis established regarding the effort made by the LSSGSs (distribution or retailers) to maintain these PPs within a psychological price range for the end consumer, increasing them according to the trend of the OPs, but in a smaller proportion.

Theoretically, the costs of both links and their margins should follow the concept of reasonable and coherent proportionality, but this does not seem to be the case, since in the face of OP increases of 90.31%, the PP increased by 41.56%. It could be interpreted that this difference in the speed of price growth (asymmetry) could be due to the concept of economies of scale, where the higher the volume of sales and, therefore, of purchases, the lower the production costs, but even without data on the volume of purchases by distributors, it is highly improbable that when a product becomes more expensive, demand will increase, unless it is a Giffen good, which is not the case of olive oil. As it is a standard and basic good in the shopping cart, its price is a reference for the end consumer and, hence, the effort of distribution not to pass on the increases in OPs at 100%. This fact is the second indication that could explain the use of the PP of virgin olive oils as an attraction product by the retailers.

This last consideration transfers to the study the concept of price elasticity of olive oil, where the Price and Market Observatory of the Andalusian Regional Government (Observatorio de Precios y Mercados, 2013) establishes that the consumption of virgin olive oils in Spanish households is influenced by two fundamental variables, price and family income, with a similar weight in both, although with opposite signs and with the importance of income being slightly higher. It also considers that it has the characteristic of normal goods and that demand is inelastic to price, i.e., an increase in price implies a proportionally lower reduction in consumption. Consequently, it is shown that in the face of OP increases, PPs do not rise in the same proportion because the consumer would stop buying. Therefore, the differences between PP and OP decrease.

At the statistical level, the data obtained show a positive correlation between the OP and PP price variables with an index of $r = 0.82$, which indicates a strong correlation between both variables. While the correlations between virgin oils yields per campaign and the OP and between the same yields and the PP are very different and neither of the two is conclusive. Thus, the correlation index between production and OP is inverse with an index $r = -0.0088$ and indicates a null correlation between both variables, while for production and PP it is direct with an index $r = 0.1365$ with a slightly higher correlation, but also practically non-existent.

Table 5 - Construction of costs and margins for packers and distributors for extra virgin olive oil.

Campaigns	*Packers*		*Distributors*		*Total link*
	Cost (€/kg)	*Margin (€/kg)*	*Coste (€/kg)*	*Margin (€/kg)*	*Packers & Distributors (€/kg)*
2018/2019	0.470	0.187	0.270	0.392	1.319
2019/2020	0.470	0.499	0.272	0.186	1.427
2020/2021	0.514	0.206	0.282	-0.231	0.771
Average	*0.485*	*0.297*	*0.274*	*0.116*	*1.172*

Source: own elaboration based on Observatorio de la Cadena Alimentaria (2021a, 2021b and 2023).

The coefficient of determination between the variables PP and OP shows an index of $R^2 = 0.6739$, which is an acceptable adjustment, with a certain predictability in the behavior of both variables.

As for the relationship between annual productions of virgin olive oils and PPs, there is practically no correlation. There is even less correlation between these same annual productions and the OPs. This may confirm and reinforce the hypothesis of asymmetry in the subsector mentioned above, since the olive mills have no control or capacity to influence on prices even when harvests are below average, while the distributors have more capacity to set prices with very different annual productions. This circumstance gives rise to the fourth indication, which points to the distribution as the main player in the value chain in terms of determining the PP following its own interests and strategy for attracting end consumers.

Finally, comparing the data of the present study with the data provided by the Agrifood Chain Observatory (Observatorio de la Cadena Alimentaria, 2021a, 2021b and 2023), the results confirmed the hypothesis that the difference between the PP and the OP is not high sufficient to be able to allocate the costs and profit margins of packers and distributors, with distributors being the most likely to fail to do so.

This is justified through the simulation carried out with the data from both studies, where the results obtained indicate that for the packaging and distribution links, the costs and profit margins of extra virgin olive oils for the 2018/2019 campaign were 1.319 €/kg, for 2019/2020 1.427 €/kg and for 2020/2021 0.771 €/kg.

These costs and margins from the Agrifood Chain Observatory (Observatorio de la Cadena Alimentaria, 2021a, 2021b and 2023), were cross-referenced with the difference between the PP and OP for the extra virgin category of the three campaigns (2018/2019, 2019/2020 and 2020/2021), establishing the assumption that the packaging link allocated 100% of its costs and margins. In this way, it was possible to analyze whether the amount in euros that remained covered the costs and profit margins of distribution.

The result obtained establishes that for the 2018/2019 campaign the distribution was able to allocate a margin to the extra virgin oil sold of 0.293 €/kg, while for the 2019/2020 and 2020/2021 campaigns, not only were they not able to allocate their margin, but this difference did not even cover their costs. The simulation estimated a negative margin for distribution for these two campaigns of -0.101 €/kg and -0.112 €/kg respectively.

In view of the above, it would be the distribution that acts strategically with the PP of extra virgin olive oils, confirming the hypothesis put forward at the beginning of this paper.

Currently, the future outlook for the euro zone is very uncertain. The arrival of Covid-19, the war in Ukraine and political instability in some European countries has led to an environment of high interest rates and inflation. In this regard, over the last year and a half, the Spanish government has implemented public policies aimed at reducing inflation by lowering VAT on certain food items, including olive oil.

We consider that the new inflation rates, although they are gradually decreasing, will allow us to pass on a new reference price to the end con-

Table 6 - Estimated distribution margin for extra virgin olive oils.

Campaigns	*Packers*		*Distributors*	*Total link (€/kg)*	*OP €/kg*	*PP €/kg*	*Difference OP&PP (€/kg)*	*Estimated Margin Distributors (€/kg)*
	Cost (€/kg)	*Margin (€/kg)*	*Cost (€/kg)*					
2018/2019	0.470	0.187	0.270	0.927	2.53	3.75	1.22	0.293
2019/2020	0.470	0.499	0.272	1.241	2.12	3.26	1.14	-0.101
2020/2021	0.514	0.206	0.282	1.002	2.95	3.84	0.89	-0.112
Average	*0.485*	*0.297*	*0.275*	*1.057*	*2.53*	*3.61*	*1.08*	*0.027*

Source: own elaboration based on Observatorio de la Cadena Alimentaria (2021a, 2021b and 2023).

sumer. This will allow producers and olive mills to maintain their OPs, improving their profitability and causing the distribution to pass on the real cost of the OPs to their PPs, establishing a new reference price for olive oils in the mindset of the end consumer. If this hypothesis becomes a reality and is sustained over time, distribution will have no choice but to change its strategy.

6. Conclusions

The conclusions obtained reinforce the hypothesis of the strategy followed by the distributors to control PP and not to pass on 100% of the OP increases. Likewise, distributors are not imputing part or all of the costs and may be consciously incurring losses for the sake of a customer acquisition strategy. Distribution with very uneven production campaigns manages to maintain price differences, controlling PP and putting pressure on OPs. All this reinforces the hypothesis of asymmetry and distribution control over the PP of virgin olive oils.

The analysis of correlations confirms the hypothesis of asymmetry of the subsector mentioned above, since olive mills have no control or capacity to act on prices even when harvests are below average, while distributors have more capacity to establish prices with very different productions. These figures argue that production levels may not be as decisive for price setting as it could be thought at first.

Finally, the model simulation estimated a negative margin for the distributors for two of the three campaigns analyzed. There seems to be, therefore, a price range in which the distributor wishes to maintain the price of virgin olive oils, considering it the optimal price to trigger the final consumer’s purchase.

The conclusions drawn confirm the hypothesis of the control and maintenance of the PP of virgin olive oils by the distributors, which makes it feasible to use them as a “lure product” or “loss leader”, even when incurring possible losses. The main conclusion is that the setting of the PP of virgin olive oils is based more on a commercial strategy than on a correct sequence of prices and margins along the value chain. It shows that there is an asymmetric price transmission system.

This paper is not free of limitations. The first is that it is focused on Spain and on a specific product, so in the future it is considered as other possible lines of research to reproduce it in other countries and other sectors. The second is the lack of knowledge of the stock management criteria followed by bulk and packaged virgin olive oils because there is no published data on the subject, which could have repercussions on pricing.

We believe that the results can help those involved in the value chain to better understand the construction of the price of virgin olive oils and establish future pricing strategies to improve their profitability, especially for producers. It is necessary to generate a stronger chain in which all the links collaborate and have profits, even more so in a scenario of reduced CAP subsidies that would make many olive groves economically unviable. Paradoxically, the leading product of the Mediterranean is threatened by the malfunctioning and lack of collaboration of the different links in the chain.

Thus, a further step is taken in demonstrating the need for political action against this type of actions that endanger the permanence and continuity of producers (the weakest link in the value chain), with the importance that this implies for the economic development of rural areas, the setting of the population in these demographically disadvantaged environments, the maintenance of biodiversity and the environment. One of the main policy implications of the study is to provide Law 16/2021 on the agrifood chain with a certain value (0.95 €/kg) to reinforce it, trying to stop sales at a loss and to transfer a new reference price in the market.

For industry professionals, the study has shown that the main problem of OPs is in the PPs. In other words, the distribution strategy to keep PPs in low environment puts pressure on OPs, causing them not to reflect the real production cost. This situation of weakness may end up affecting all those involved in it.

On the academic side, our paper has contributed to establish a new figure in the value chain for the last two links that will help to improve its functioning and will lay the groundwork for further studies. Researchers could help in this area by continuing to develop studies of the chain and each link and apply it to other countries and sectors.

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Exploring the nutritional and nutraceutical significance of legumes: A comparative analysis across Mashreq countries

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Abstract

This study investigates the nutritional and nutraceutical profiles of four legume species - bean, faba bean, chickpea, and lentil - collected from Lebanon, Syria, Jordan, Palestine, and Egypt. Chemical analyses assessed antioxidant, nutritional, and nutraceutical properties, followed by Principal Component Analysis and Hierarchical Cluster Analysis to examine similarities and differences among legume varieties and regions. Key findings include Lebanese beans with distinct tocopherol (vitamin E), polyphenols, flavonoids, and TEAC, along with high protein, lysine, and methionine. Syrian faba beans showed superior vitamin E, TEAC, protein, lysine, and methionine levels, while a Palestinian variety excelled in polyphenols and flavonoids. Syrian chickpeas were rich in vitamin E, flavonoids, protein, and methionine, and a Palestinian variety stood out for histidine and lysine. Lentils from Lebanon, Syria, and Palestine had notable vitamin E and methionine contents. These findings highlight the role of genetic, environmental, and geographical factors in legume quality, emphasizing their potential in addressing malnutrition and promoting sustainable food systems.

Keywords: *Nutritional profile, Nutraceutical characteristics, Legumes, Chemometric analysis, Food security, Mediterranean diet, Mashreq Countries*

1. Introduction

The Mashreq region, which includes Lebanon, Syria, Jordan, Egypt and Palestine, faces significant economic political and security challenges stemming from conflicts, poverty, unemployment, and displacement. These difficulties have led to malnutrition, food insecurity, and limited access to balanced diets, especially affecting vulnerable groups such as refugees, internally displaced persons, women, and children (Capone *et al.*, 2021). One of the most pressing nutritional issues is ensuring enough high-quality proteins, which remains a primary focus of nutritional interventions in the region. Access to high-quality animal protein sources remains

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challenging for low-income communities due to limited economic resources. However, partially replacing these protein sources with legumes can offer numerous benefits for both individuals and the community as a whole. Legumes boast high nutritional value, being rich in protein, fiber, vitamins, and minerals, making them a valuable alternative to meat. They provide essential nutrients crucial for growth, development, and overall health, which may be deficient in the diets of low-income individuals. Moreover, legumes are cost-effective, sustainably produced with a lower environmental footprint, and offer health benefits by reducing the risk of non-communicable diseases (NCDs).

Legumes constitute a staple source of nutrition in the traditional Mediterranean Diet (MD) (Sikalidis *et al.*, 2021). The main legumes consumed in the Mediterranean region include faba beans (*Vicia faba* L.), chickpeas (*Cicer arietinum*), lupins (*Lupinus albus*), and lentils (*Lens culinaris*) (Godos *et al.*, 2024). These versatile crops are renowned for being nutrient-dense and possessing health-promoting properties (Amoah *et al.*, 2023). They are rich in protein, complex carbohydrates, fibers, vitamins, minerals (Montejano-Ramírez and Valencia-Cantero, 2024), low in fat, cholesterol-free, and have a low glycemic index (Amoah *et al.*, 2023; Vijayakumar and Haridas, 2021). It is important to note that, with the exception of soybeans, legumes should be combined with grains to form a complete diet, rich of all essential amino acids (Lisciani *et al.*, 2024). Beyond their nutritional value, legumes have nutraceutical properties, as they contain numerous bioactive compounds, including polyphenols (flavonoids and non-flavonoids) and phytosterols (Ganesan and Xu, 2017).

Various studies have highlighted the positive health outcomes associated with legume consumption, including decreased risk of type 2 diabetes mellitus, cardiovascular diseases, and certain cancer types (Yanni *et al.*, 2023). Moreover, legumes are recognized for their anti-inflammatory, antihypertensive, and antioxidant properties (Naureen *et al.*, 2022). In addition to these health benefits, legumes have a low environmental footprint and can be grown in a variety of climates and soil types, making them a sustainable option for farmers (Yanni *et al.*, 2023). Thus, a protein-rich diet based on legumes is a feasible, cheaper, and sustainable alternative to animal-based diets and helps prevent malnutrition in developing countries (Lisciani *et al.*, 2024; Montejano-Ramírez and Valencia-Cantero, 2024). Despite that, the global legume intake, being around 21 g/person/day (Semba *et al.*, 2021), is substantially lower than the recommendation of ~100g of cooked legumes by EAT-Lancet and MD (Hughes *et al.*, 2022).

Research has shown that phenolic content could vary between different varieties of legume species due to genetic factors, climatic conditions, storage, and variation in color of coats between cultivars (Carbas *et al.*, 2020; Yang *et al.*, 2018), as well as degree of maturity (Marathe *et al.*, 2011). Moreover, the geographic location where legumes are grown influences their nutraceutical and nutritional content (Johnson *et al.*, 2021; Shea *et al.*, 2024) due to environmental factors such as soil composition, annual rainfall, altitude, and humidity (Yegrem, 2021). As such, within legume species to have the highest nutritional and antioxidant profiles is crucial for maximizing the benefits deriving from their consumption.

The multivariate method includes Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA) and Partial Least Squares Regression (PLS) are useful tools in science for classifications (Al Bakain *et al.*, 2020, 2021; Belharar and Chakor, 2023). These tools were performed in analytical studies for many purposes; to identify the most relevant compounds in distinguishing legumes varieties, to find the variation in chemical profiles as a result of growing legumes in different batches and with variations in growth locations, to confirm whether the cultivars in the cluster analysis would also be grouped together, to reveal the compounds that were responsible for grouping cultivars between clusters and to predict the geographical origin of the sample using linear discriminant analysis.

The Mediet project has been launched in 2022 by the International Center of Advanced Mediterranean Agronomic Studies of Bari (CIHEAM-Bari) and funded by the Italian Ministry of Foreign Affair and International Cooperation (MAECI), aims to address Sustainable Development Goal (SDG) number 2, Zero Hunger, by promoting legume production and consumption. The project focuses on the role of legumes in improving food security, nutrition, and sustainable agricultural practices, particularly in Mediterranean regions. This paper presents the initial findings of the project, relate to the nutritional and nutraceutical analysis of four legume species, which serve as a critical component of the project's broader objective. Using advanced multivariate statistical methods, results were analyzed to identify and select legume samples that exhibit promising nutritional and nutraceutical properties. The obtained results are addressed to improve consumer's awareness about the main nutritional and nutraceuticals benefits achievable by the legume consumption. The findings hold potential implications for public health and agricultural policy, as they can inform strategies to promote sustainable diets and enhance food security through the increased consumption of selected legumes. The final goals are to improve dietary diversity, reduce malnutrition, and ultimately foster better health outcomes in both local and global contexts.

2. Materials and methods

2.1. *Legumes samples*

Forty-seven dry seeds represent local cultivars and selected varieties of four legumes: bean, faba bean, chickpea, and lentil were collected during 2022 and 2023 from various locations in Lebanon, Syria, Jordan, Palestine, and Egypt. These regions are known for their long-standing tradition of legume cultivation and their integration of legumes into crop rotation systems. The selected varieties are highly valued by farmers for their productivity and economic benefits, as well as by markets for their competitive prices, which are driven by strong consumer demand. Most of the pulse varieties were developed by ICARDA and National Research Systems in the Mashreq countries and have been widely adopted by farming communities. Meanwhile, local cultivars are either the result of institutional breeding programs or derived from seasonal multiplication by local producers.

2.2. *Extraction method, Samples preparation, Running conditions and Instrumentation*

The dry seed samples were ground using an electric grinder to produce a homogeneous powder capable of passing through a 35-mesh stainless steel sieve with a 0.5 mm opening size. Dry matter content was determined by drying the powdered sample in static oven at 105°C until constant weight reached according to the AACC Method 44-17.01. Ash content as percentage was determined according to the AACC Method 08-16.01 by incinerating the residual obtained for dry matter content in muffle at 550°C. The extraction method, sample preparation, running conditions and the instrumentation were explained separately in the next sections.

2.2.1. *Centesimal composition determination of total Protein and Fat*

Total proteins, expressed in g per 100 g of seeds, was determined according to the AOAC Method 992.23 based on the Dumas method and using a carbon/nitrogen analyzer PRIMACS ™ SNC-100 (Scalar, The Netherlands) and the conversion factor nitrogen-proteins of 5.71. Total fat content was determined by solid liquid extraction using a Soxtec™ system model 2050 (Foss, Denmark), petroleum ether 40-60° as extraction solvent, and expressed as gram per 100 gram of dry seeds.

2.2.2. *Amino acids content*

The quantitative determination of proteinogenic amino acids was performed by the application of three different types of hydrolysis: HCl 6N after oxidation with performic acid for the determination of sulfur containing amino acids (i.e. cysteine and methionine); NaOH 4N for tryptophan determination and HCl 6N for all remaining amino acids. All hydrolysis processes were performed in amber borosilicate vials under N_2 in presence of pyrogallol as antioxidant at 110°C per 24hr using a block heater with temperature control. After hydrolysis, 100nmol of norleucine was added as internal standard, then samples were neutralized, diluted with ultrapure water, analyzed by ions chromatography and post column derivatization with ninhydrin using the amino analyzer Biochrom 30+ (Harvard Bioscience, USA). The concentration of each amino acid was calculated using internal calibration method. The calibration curves were obtained by the injection of 5 levels of calibration from 5 -500 nmol/mL of a standard mix (Protein hydrolysate standard mix, Biochrom) in triplicate.

2.2.3. *Total polyphenols, flavonoids and antioxidants contents*

Polyphenols compounds were extracted from the powder of dry seeds obtained as described in sample preparation and extraction methods section (2.2). The extraction solution was acetone: water: acetic acid (70:29.5:0.5 by volume). An aliquot of 2.0 g of powder samples was weighed in 50 mL centrifuge tubes, then 20 mL of the extraction solution was added, sonicated for 15 min at ambient temperature, orbitally shaken for 2hr, and finally centrifuged at 4000 RCF for 10 min at 10°C. After centrifugation, the clear upper phase was recovered, whereas the pellet was re-suspended in 20 mL of the extraction solution and the whole procedure repeated again. The two extracts were mixed, filtered at 0.45 μm regenerated cellulose filters and stored at 4°C for the next assays.

Twenty microliters of sample extract were used for the Folin micro assay according to (Wrolstad *et al.*, 2005). Calibration was done using gallic acid standard in the range 10-400 mg/L. Results were expressed as mg of gallic acid equivalent per 100 g of dry seeds. The antioxidant activity was performed using the extract obtained for the determination of total polyphenols. The assay used was the ABTS calibrated with Trolox. The ABTS radical solution was obtained by mixing 10 mL of ABTS 7mM with an equal volume of persulphate 4.95 mM. The mixture was left at room temperature in the dark for 12h, then stored in refrigerator for a maxim of 3 days. Using the stock solution of ABTS radical, a dilution was prepared, obtaining an absorbance at 730nm of approximately 0.7 absorbance units. The calibration range was 25-800 nmol/mL of TROLOX. In plastic cuvettes of 1.5 mL total volume, 980 μL of ABTS diluted radical solution was placed and added to 20 μL of sample extract or standard solution. The cuvettes were closed using parafilm, mixed for 25 min and then, the absorbance was measured. The difference in absorbance between the cuvette containing the sample extract and that containing only the extraction solvent as blank was calculated and used to express the final concentration as μmol of Trolox Equivalent Antioxidant Capacity (TEAC) per 100 g of dry seeds.

Total flavonoids determination was performed by colorimetric method using $AlCl_3$ and $NaNO_2$ reagent, according to (Heimler *et al.*, 2005). Catechin was used as reference standard with a calibration range 10-500 mg/L. Results were expressed as mg of catechin equivalent per 100 g of dry seeds.

2.2.4. *Vitamin E*

Vitamin E as total tocopherol was determined according to the method ISO 9936, by alkaline hydrolysis in presence of pyrogallol as antioxidant under nitrogen, followed by liquid – liquid extraction with petroleum ether at 40-60°C. The obtained extract was concentrated under vacuum and re-suspended in 1.0 mL of isooctane containing 0.2% of butylhydroxytoluene. Twenty microliters of this solution were injected into a High Performance Liquid Chromatography (HPLC) system. The HPLC system consisted of a normal phase isocratic pump LC-40D equipped with a fluorescence detector RF-20A XS (Shimadzu, Kyoto, Japan). The mobile phase used was hexane with 1% dioxane under isocratic elution of 1.0 mL/min flowrate. The stationary phase was Zorbax RX-Sil of 100 mm × 3.0 mm I.D with 1.8 μm particles diameter. A calibration curve was obtained by the injection of five concentration solutions of α-tocopherol pure standard in a range 0.1-10 μg/mL. Results were expressed as mg of α-tocopherol equivalent per 100 g of dry seeds.

2.2.5. *Sterols*

The unsaponifiable matter was obtained from the total fat extracted with Soxtec apparatus as described before, submitted to a saponification with ethanolic KOH 0.2N and then to liquid-liquid extraction according to the AOAC Official Method 933.08. A 5α-cholestanol as an internal standard was added to the unsaponifiable matter, then the sample was analyzed by tin layer chromatography (TLC) to separate and purify the sterols fraction.

Finally, sterol's fraction obtained by TLC was derivatized using a silylating mixture and subjected to gas chromatographic-flame ionization (GC-FID) analysis. The Nexis 2030 GC system was equipped with autosampler AOC-20i Plus (Shimadzu), column SPB-5 (Supleco 30 m × 0.25 mm I.D, 0.25 µm film thickness). The separation of sterols was performed at the following conditions: isothermal condition of 265°C, injector temperature at 280°C, split mode of 1:25, detector at 300°C and hydrogen as carrier gas at constant velocity of 35 cm/s. Results were expressed in mg/100g of dry seeds.

2.2.6. *Fatty acids*

The total fat extracted by the soxtec apparatus was trans methylated by cold method with KOH 2N in methanolic solution. The methylated fatty acids were injected into the GC system described above, equipped with a DB-Fast FAME column (Agilent 20 m × 0.18 mm I.D, 0.20 µm film thickness). The chromatographic conditions were: H_2 as carrier gas at constant velocity of 35cm/s, injector temperature of 230°C, split ratio 1:50, initial temperature 80°C increased to 175°C at 65°C/min, then increased to 185°C at 10°C/min, increased to 230°C at 7°C/min, finally isothermal for 3 min. The quantitative results expressed in mg/100g of dry seeds were obtained by applying an external calibration method using FAME 37 standard mix at five levels of concentrations analyzed using the same chromatographic conditions of samples.

2.2.7. *Mineral elements and phosphorus*

Mineral elements were analyzed accordingly to the method AOAC 984.27 with wet mineralization process using Ethos Easy Microwave Digestion System -Milestone (Bergamo, Italy), followed by Inductively Coupled Plasma Atomic Emission Spectroscopy analysis using a spectroscope model iCAO 6000 Thermo Fisher Scientific (Waltham, Massachusetts, U.S.).

2.3. *Statistical software*

Data acquisition and processing were conducted using MS Workstation software version 6.6 (SP1). The statistical analysis including PCA and HCA were performed using Chemoface 1.61 software which work under Matlab® (Mathworks, 8.6, USA) and *XL*STAT software (Excel, Microsoft®).

3. Results

3.1. *Multivariate analysis of legumes samples using unsupervised clustering methods*

Initially, the analytical results obtained from the whole analysis (Appendix 1) was arranged in a data matrix $X_{n \times l}$, where *n* is the number of samples (i.e. number of locations for each species) and *l* is the number of measured variables (i.e. solutes: faba beans, beans, chickpea and lentil). The total number of samples was 47 represents 47 locations of 5 countries; Jordan, Lebanon, Syria, Egypt and Palestine. For the current system, matrix X had the size of (12×18), (17×18), (14×18), (4×18) for faba beans, lentils, chickpeas and bean, respectively. Matrix *X* was subjected to clustering methods as will be discussed below. None of the collected samples were not priori assigned to class membership; hence, unsupervised clustering methods will be applied.

3.2. *PCA and HCA*

The main adopted unsupervised methodologies in analytical chemistry for grouping/clustering objects are PCA and HCA (Abu Mualla and Al Bakain, 2023; Al Bakain *et al.*, 2020). In this study, HCA and PCA were implemented to: 1) confirm whether the legumes obtained from different cities would be grouped together based on their 18 chemical contents, or 2) the resulted chemical contents would be grouped together according to their similar/different concentrations in each species. In fact, PCA reveals the chemical contents that are responsible for grouping the samples. This classification results may have value in the discrimination and selection of legumes species in certain locations. The results may help to show the similarities and the differences between legumes profiles (faba, lentil, chickpea and beans) cross the big producers and consumers of these legumes (i.e. Lebanon, Jordan, Palestine, Syria and Egypt).

3.3. *Legumes characterization by PCA and HCA*

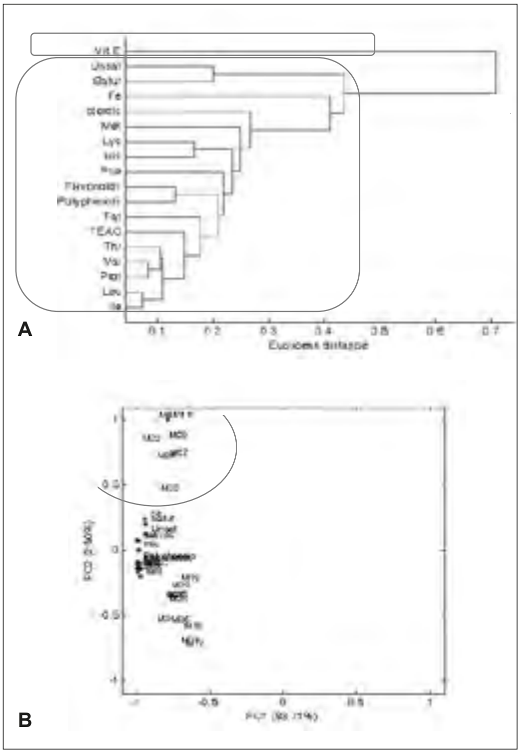
Both PCA and HCA are performed to confirm whether the legumes species obtained from different locations would be grouped together based on the 18 nutritional parameters measured (total fat, protein, Fe, sterols, vitamin E, polyphenols, flavonoids, TEAC, histidine, methionine, lysine, leucine, phenylalanine, valine, threonine, isoleucine, saturated and unsaturated fat). PCA can reveal the variables that is/are responsible in grouping legumes. Legumes classification will be the foundation for industrial production, and informative guidance for individual growers. Indeed, these results would help to show the similarities and the differences between legumes-origin samples of some Arab countries that are considered as big producers and consumers of legumes.

- *Arrangement of analytical data*: Analytical data can be arranged as a data matrix X of n samples or location rows and l variables. For the current case, matrix X has the size of 18 (solutes) × n locations (12, 17, 14, and 4 for faba, lentil, chickpea and beans, respectively), and matrix X has the size of 18 (solutes) × 4 species (faba, lentil, chickpea and beans). Matrix X was subjected into HCA and PCA as discussed below. Data was preprocessed using normalizing methodology, which allowed for better and interpretably PCA outputs.

- *Quantitative legumes classification by PCA and HCA*

In this study, two data matrices where built. The data matrix X (18×n) (i.e. 18 solutes from n locations) is decomposed into two matrices, T (score matrix) and L (loading matrix) using suitable PCA algorithm. The first step in PCA is the computation of loadings. Mathematically, the loadings are the Eigen vectors of the matrix (XXT). There are several methods to estimate the eigenvectors, such as singular value decomposition (SVD) and NIPALS (non-linear iterative partial least-squares) in the order of explained proportion of the variations in X, until a certain pre-established number of components (Al Bakain *et al.*, 2021). The loadings are

Figure 1 - A) Dendrogram based on average linkage clustering and B) PCA bi-plot obtained from the 17 origin- lentil components from Syria, Egypt, Palestine, Jordan and Lebanon.



grouped into a matrix L. The collected loadings are orthonormal, meaning that they are both orthogonal and normalized. The relationship between the original matrix X, the loading matrix L and the score matrix T is described as:

$$X = TLT \qquad \text{Eq. 1}$$

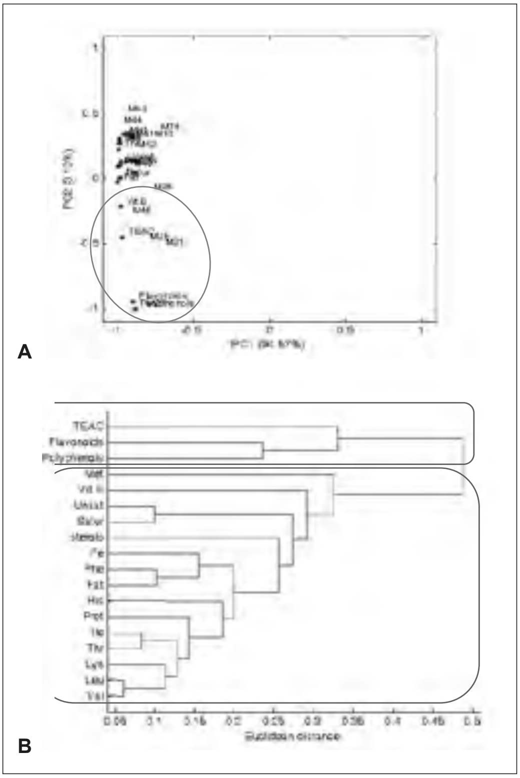
Mathematically, matrix X is decomposed in the product of two matrices, T and L, on the condition that L is formed by orthonormal columns. T is the obtained as: $T = XTL$. In this work, size of X is 18×18 while size T is 18×h and L is h×18, where h is the number of factors needed to decompose matrix X. The optimum number of factors (h) is necessary to create optimum number of loadings and scores and produce informative discrimination among samples/legumes. The analytical scan data were subjected to HCA and PCA analysis. PCA and HCA are commonly employed to reduce the complexity of multivariate data sets without losing important information, observe variance in data sets, and visualize data clustering (Al Bakain *et al.*, 2020). In this study, 18 chemical contents are the original variables (18 dimensions) in PCA. By calculating the covariance matrix between these 18 dimensions, PCA can generate 18 PCs that are orthogonal to each other and can explain 100% of the total variance of the orthogonal data. Each PC is correlated with the original 18 variables. All detected chemical contents were rather necessary for legumes clustering. Accordingly, the number of variables used in clustering was 18 (detected solutes) × n (locations) for each species.

As noticed in the 17 lentil samples results (Figure 1), Vitamin E is the main content responsible for grouping samples M7, M9, M22, M24, M33 and M47. Referring to Appendix 1, these locations showed distinguished contents of vitamine E. Two main clusters collect the 18 contents; cluster A collects only vitamin E, and cluster B collects the remaining variables.

Regarding the faba samples, the PCA and HCA outcomes in Figure 2, reveal that (M21, M25) (M23) and (M46) have distinct contents of (TEAC), (polyphenols, flavonoids, TEAC) and (vitamin E), respectively.

According to chickpea, the outcomes of PCA in Figure 3, reveal that M30, M31 and M45 have distinguished content of vitamin E, in addition to flavonoids in M30 and histidine in M45.

Figure 2 - A) PCA bi-plot and B) Dendrogram of the 18 chemical contents obtained from the 12 origin- faba from Syria, Egypt, Palestine, Jordan and Lebanon.



For Bean, M5 showed distinguished contents of vitamin E, polyphenols, flavonoids and TEAC, whereas M1 have distinct content of TEAC as presented in Figure 4.

Figure 3 - PCA outcomes: A) score and B) loading plots obtained from the 14 origin- chickpea components from Syria, Egypt, Palestine, Jordan and Lebanon.

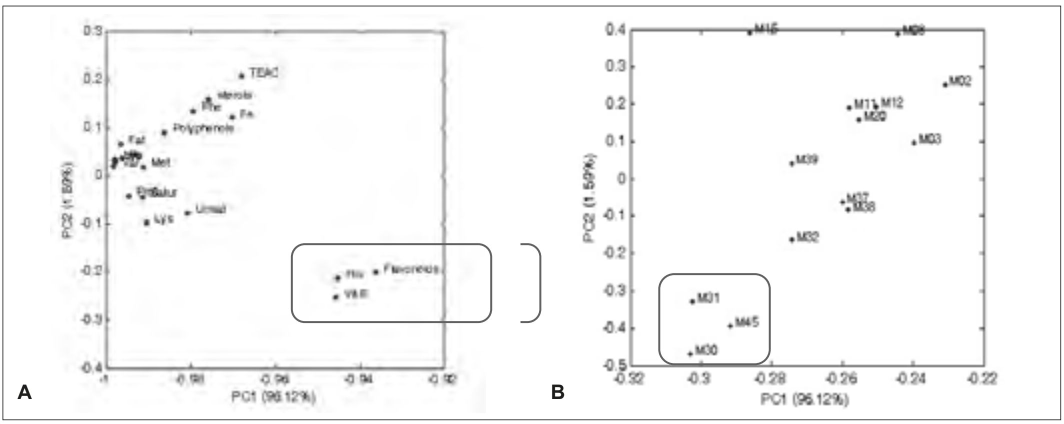
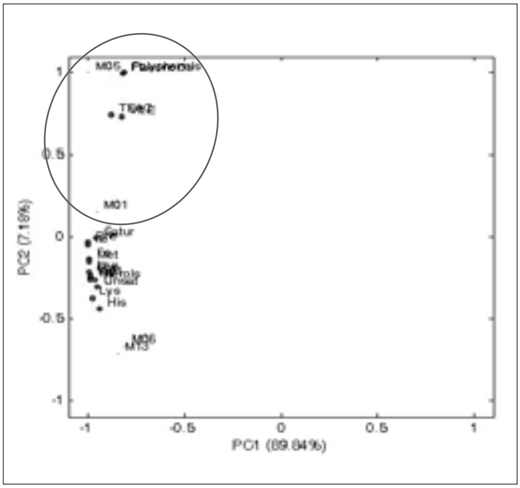


Figure 4 - PCA bi-plot obtained from the 4 origin-bean contents.



As shown in the results of the PCA outcomes, 2 PCs account 96.21%, 97.67%, 97.71% and 97.02% of the total variance in data for lentil, faba, chickpea and beans, respectively.

3.2. *Nutritional profile*

From the statistical analysis outcomes presented in the previous section, the distinguished varieties responsible for grouping and clustering were selected to reveal numerically their distinct contents, as shown in Table 1.

For beans, M01 and M05 originated from Lebanon have distinct content of TEAC reaching approximately above 50% of average effective dose. Moreover, M05 has prominent content of vitamin E that is almost close to dietary reference intake (DRI) of Alpha-tocopherols, polyphenols, and flavonoids close to or higher than the estimated effective levels of these antioxidants. Regarding M01, it had the highest protein content, contributing around one-third or more of the protein recommended dietary allowance (RDA) for males and females, respectively. For lysine content, the selected varieties could provide approximately 50% or more of the RDA. On the other hand, M05 had the highest methionine content, providing close to one-fifth or more of the requirement.

As for faba beans, four varieties were selected: M21, M23, M25, from Syria, and M46 from Palestine. M46 had 1) distinguished contents of vitamin E that is above 50% of the DRI of Alpha-tocopherols, 2) the highest protein content of around 50% or more of the RDA, 3) highest methionine content, which is around 15% of its requirement, and 4) highest lysine content, which satisfies most of the lysine RDA. M23 had prominent contents of total polyphenols and flavonoids, both higher than the estimated effective levels of these antioxidants, whereas M23, M21, and M25 have distinguished content of TEAC reaching above 50% of average effective dose.

Regarding chickpea, three varieties out of 14 were selected for their antioxidant and amino acid profiles; M30 and M31 from Syria and M45 from Palestine. These three varieties had significant contents of vitamin E both close to or higher than the DRI of Alpha-tocopherols. M30 had significant content of flavonoids approximately 30% of the effective dose of these antioxidants, the highest protein content, contributing around 50% or more of the RDA, and highest methionine content providing around 25% or more of the requirements. While M45 had significant content of histidine surpassing the recommended dietary allowance (RDA) of this essential amino acid, and highest contribution to lysine providing around 80% and 99% of the RDA for males and females, respectively.

As for lentil, two varieties from Lebanon (M7, M9), three from Syria (M22, M24, M33), and one from Palestine (M47) had distinguished vitamine E content, which is around third to half the DRI of Alpha-tocopherols, and the highest contribution to methionine, providing around 15% of the requirement. M33 had the highest contribution to protein, providing more than 50% of the RDA, and the highest lysine content close to or higher than the RDA for males and females, respectively.

Among the tested legume species, Vitamin E and histidine were the highest in chickpea, whereas total polyphenols and TEAC were the highest in faba beans, and flavonoids were the highest in beans. Protein and lysine were the highest in lentil, while methionine was the highest in chickpea.

Table 1 - Antioxidant and nutritional profiles of the selected significant varieties of legume species from Lebanon (LB), Syria (SY), and Palestine (PA) (results are expressed per 100g raw seeds).

Requirement of Nutrient or Effective Dose of Nutraceutical		*Dietary Reference Intake: 15mg/d alpha-tocopherol*	*Effective dose: >1170mg/d[*]*	*Effective dose: 500mg/d[†]*	*Effective dose: >5540µmol/d[‡]*	*Recommended Dietary Allowance: Females: 798mg/d Males: 980mg/d[§]*	*Recommended Dietary Allowance: Females: 46g/d Males: 56g/d[¶]*	*Requirement: Females: 593mg/d Males: 728mg/d[#]*	*Recommended Dietary Allowance: Females: 2166mg/d Males: 2660mg/d[§]*
Beans		*mg/100g*	*mg/100g*	*mg/100g*	*mg/100g (µmol/100g)*	*mg/100g*	*g/100g*	*mg/100g*	*mg/100g*
LAB code	*Orig. Code#*	*Total tocopherol Vitamin E*	*Total Polyphenols gallic acid Equivalents (GAE)*	*Flavonoids catechin equivalent (CE)*	*Trolox equivalent antioxidant capacity (TEAC)*	*Histidine*	*Protein*	*Methionine*	*Lysine*
M01	LB01	2.15	829.97	548.67	**721.09 (2881)**	466.01	18.65	122.24	1332.29
M05	LB05	**12.77**	**1165.01**	**831.03**	**720.50 (2879)**	470.88	17.54	133.27	1061.59
Faba bean									
M21	SY 007	4.23	950.60	380.61	**926.87 (3703)**	578.15	25.15	96.41	1519.58
M23	SY009	5.45	**1387.14**	**588.11**	**924.25 (3693)**	415.93	22.93	84.99	1189.96
M25	SY011	6.30	881.29	423.70	**756.75 (3023)**	596.78	24.00	96.90	1593.13
M46	PA02	**8.40**	954.63	370.68	658.80 (2632)	916.75	25.83	99.68	1717.53
Chickpea									
M30	SY016	**14.85**	88.05	**136.28**	53.57 (214)	741.37	27.72	185.33	1853.81
M31	SY017	**16.31**	88.01	99.04	67.28 (269)	753.90	24.43	173.99	1802.79
M45	PA01	**17.42**	116.72	46.20	73.94 (295)	**1391.54**	20.93	178.37	2138.61

Requirement of Nutrient or Effective Dose of Nutraceutical		*Dietary Reference Intake: 15mg/d alpha-tocopherol*	*Effective dose: >1170mg/d**	*Effective dose: 500mg/d†*	*Effective dose: >5540µmol/d‡*	*Recommended Dietary Allowance: Females: 798mg/d Males: 980mg/d§*	*Recommended Dietary Allowance: Females: 46g/d Males: 56g/d¶*	*Requirement: Females: 593mg/d Males: 728mg/d#*	*Recommended Dietary Allowance: Females: 2166mg/d Males: 2660mg/d§*
Lentil		*mg/100g*	*mg/100g*	*mg/100g*	*mg/100g (µmol/100g)*	*mg/100g*	*g/100g*	*mg/100g*	*mg/100g*
LAB code	*Orig. Code#*	*Total tocopherol Vitamin E*	*Total Polyphenols gallic acid Equivalents (GAE)*	*Flavonoids catechin equivalent (CE)*	*Trolox equivalent antioxidant capacity (TEAC)*	*Histidine*	*Protein*	*Methionine*	*Lysine*
M07	LB07	**6.99**	1193.52	592.52	707.83 (2828)	613.24	21.55	101.54	1440.43
M09	LB09	**7.63**	1002.88	459.45	694.60 (2775)	672.11	22.14	87.76	1470.98
M22	SY008	**5.34**	1323.71	491.36	930.16 (3716)	930.21	27.25	89.88	1900.01
M24	SY010	**4.92**	947.56	384.62	936.20 (3740)	789.62	24.40	97.65	1522.07
M33	SY019	**5.25**	865.65	484.30	752.72 (3007)	1018.63	30.69	91.21	2347.66
M47	PA03	**7.63**	889.56	394.99	695.94 (2780)	1244.29	24.83	102.83	1717.03

Note: Values in bold are significant. Protein and amino acid requirements for adults are based on reference weights used by the Institute of Medicine: 70kg for males and 57kg for females (Medicine, 2005).
** Overall inverse association between total polyphenol intake (above 1170 mg/day) and cardiovascular (CV) risk events and mortality (Del Bo' et al., 2019).*
† Higher dietary intake of total flavonoids is associated with decreased cardiovascular disease (CVD) risk in a linear manner, with the highest intake calculated at 500 mg/day (Micek et al.*, 2021).*
‡TEAC is inversely associated with colorectal cancer risk (La Vecchia et al.*, 2013).*
§ Histidine and Lysine recommended dietary allowance (RDA) for adults is 14 and 38mg/kg/d, respectively (Medicine, 2005).
¶ Protein recommended dietary allowance (RDA) for adults is 0.8g/kg/d (Medicine, 2005).
 # Methionine requirement for adults is 10.4 mg/kg/d (Joint et al., 2007).

4. Discussion

To the best of our knowledge, this is the first study to identify varieties of legume species (i.e., bean, faba bean, chickpea, and lentil) with superior antioxidant and nutritional profiles from several countries in the Mediterranean region, particularly Lebanon, Jordan, Egypt, Syria, and Palestine. This marks a significant step toward maximizing the health benefits of legumes and addressing malnutrition, especially in impoverished communities. Legumes are an affordable source of protein, micronutrients, and antioxidants, which are associated with reduced disease risk (Grewal *et al.*, 2022). Identifying varieties with significantly enhanced nutritional and antioxidant profiles offers a means to alleviate malnutrition and enhance public health. Additionally, bioactive compounds in legumes, such as polyphenols and flavonoids, contribute to their medicinal properties and potential as drug sources (Vijayakumar, 2021). The identified varieties could serve as parental material for breeding cultivars with enhanced nutritional profiles (Grewal *et al.*, 2022).

For beans, two varieties from Lebanon stood out for their distinguished antioxidant content, with M05 demonstrating significant levels of vitamin E near the recommended daily allowances (RDAs). Vitamin E is a potent antioxidant that has been shown to support cardiovascular health, cancer prevention, and immune function by reducing the oxidation of low-density lipoprotein (LDL) cholesterol and preventing blood clot formation (Rizvi *et al.*, 2014). Additionally, vitamin E protects cell membranes from free radical damage, inhibits carcinogen formation in the stomach (Wood and Grusak, 2007) contributes to immune function (Lewis *et al.*, 2019), facilitates DNA repair (Kaźmierczak-Barańska *et al.*, 2020), and supports various metabolic processes (Wood and Grusak, 2007). The M05 variety also exhibited high levels of polyphenols, flavonoids, and TEAC, offering antioxidant, anti-obesity, anti-diabetic, anti-inflammatory, and anti-carcinogenic properties (Ganesan and Xu, 2017). Polyphenols play a critical role in protecting organisms from external stressors and neutralizing reactive oxygen species (ROS) (Rana *et al.*, 2022). Flavonoids, a class of dietary polyphenols, are associated with numerous health benefits, including anticancer, anti-inflammatory, antiviral, neuroprotective, and cardioprotective effects (Ullah *et al.*, 2020). The flavonoid content in M05 was significantly higher than previously reported levels in other legumes and varieties (Rodríguez Madrera *et al.*, 2021).

Regarding faba beans, this study selected four varieties of faba beans from 12 different cultivars for their distinguished antioxidant profiles. The M46 variety from Palestine had the highest vitamin E content among the tested varieties, while M23 exhibited superior antioxidant capacity, including high levels of TEAC, polyphenols, and flavonoids. These findings align with studies showing that faba beans are rich in polyphenols (Johnson *et al.*, 2024) and are a good source of natural antioxidants (Chaieb *et al.*, 2011), offering protective effects against conditions such as hypertension and cancer (Turco *et al.*, 2016). Concerning chickpea, three varieties of chickpeas were selected out of 14 for their antioxidant and amino acid profiles. These varieties had significant levels of vitamin E, consistent with studies identifying chickpeas as a good source of tocopherols [50]. The M30 variety from Syria exhibited a flavonoid content higher than those reported in Turkish varieties (Macar *et al.*, 2017). Finally, five varieties of lentils from Lebanon, Syria, and Palestine were selected out of 17 for their vitamin E content, corroborating research that lentils are rich in bioactive phytochemicals, including tocopherols. Gamma-tocopherol accounts for over 92% of the total tocopherols in commercial lentil samples from Italy (Boschin and Arnoldi, 2011). These varieties could be used to improve nutritional qualities in lentil breeding lines (Riaz *et al.*, 2024).

Variations in polyphenol content among the selected varieties may be attributed to genetic factors, climatic conditions, storage, and coat color differences between cultivars (Carbas *et al.*, 2020; Yang *et al.*, 2018). For instance, dark-colored beans tend to have higher phenolic content and antioxidant capacity than uncolored varieties (Carbas *et al.*, 2020; Yang *et al.*, 2018). Environmental factors such as soil composition, annual rainfall, altitude, and humidity also influence the nutraceutical properties of legumes (Yegrem, 2021).

The protein content of the selected bean, faba bean, chickpea, and lentil varieties was consistent with ranges reported in the literature (Grewal *et al.*, 2022; Martineau-Côté *et al.*, 2022). Among the legumes, chickpeas exhibited the highest methionine content, a limiting amino acid in legumes. Meanwhile, lentils stood out for their lysine and protein content, making them ideal for creating complementary proteins when paired with grains.

By fixing nitrogen in the soil, legumes reduce the need for synthetic fertilizers, enhancing soil health and contributing to sustainable agricultural practices that align with SDG Goal 12 (Responsible Consumption and Production). Their cultivation supports local biodiversity by providing habitat and food for a variety of organisms, promoting ecosystem resilience (SDG Goal 15, reduce biodiversity lost). Additionally, the integration of legumes into agricultural systems can address SDG Goal 13 (Climate Action) by reducing the carbon footprint of farming. Policies that incentivize legume cultivation and consumption, especially among small and medium enterprises (SMEs), can drive economic growth by empowering local farmers, processors, and food producers across the Mediterranean. These SMEs are key players in developing innovative legume-based products, such as functional foods and nutraceuticals, catering to the growing demand for health-conscious and sustainable dietary options. The antioxidant, anti-inflammatory, and cardio-protective properties of legumes make them functional foods, contributing to the prevention of non-communicable diseases and aligning with global health goals (SDG Goal 3, promote healthy lives and well-being).

5. Conclusion

This study highlights the nutritional and nutraceutical richness of legumes - faba beans, lentils, chickpeas, and beans - collected from Lebanon, Syria, Jordan, Palestine, and Egypt, emphasizing their critical role in food security, sustainability, and public health. Through detailed chemical profiling and multivariate analysis, the study revealed the distinct nutritional and bioactive compound profiles of these legumes. Being rich in protein, fiber, vitamins, minerals, and bioactive compounds such as polyphenols and flavonoids, legumes are confirmed as valuable alternatives to meat, particularly for resource-constrained communities. Furthermore, the study identifies superior legume varieties that could serve as parental material for breeding programs aimed at enhancing nutritional profiles and strengthening food system resilience. Beyond their nutritional benefits, legumes play a pivotal role in sustainable agricultural practices by supporting local biodiversity and improving soil fertility. Their cultivation contributes to environmental sustainability while reducing dependence on synthetic fertilizers. By integrating legumes into national food security strategies and promoting their inclusion in the Mediterranean Diet, countries in the region can achieve nutritional, economic, and environmental resilience. These efforts reaffirm the Mediterranean Diet as a global model for health and sustainability, ensuring food sovereignty and fostering a sustainable future for generations to come.

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Appendix 1 - Chemical profiling for Faba beans, Chickpea, Beans and Lentils from Lebanon, Jordan, Egypt, Syria, and Palestine

			mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g	mg/100g
Code	**Legume**	**Country**	**Protein**	**Fat**	**Fe**	**Saturated fat**	**Unsaturated fat**	**Total sterols**	**Vit. E**	**Tot. Polyphenols gallic ac. Eq**	**Flavonoids catechin eq**	**Trolox equivalent antioxidant capacity (TEAC)**	**Threonine**	**Valine**	**Methionine**	**Isoleucine**	**Leucine**	**Phenylalanine**	**Histidine**	**Lysine**
M01	Bean	Lebanon	18002.3	1259.28	6.1	112	711	69.5	**2.1**	830	546	721	860.27	735.19	122.24	430.10	1222.59	1159.44	460.61	1332.29
M02	Chickpea	Lebanon	20840.4	5007.26	6.2	266	973	74.5	**4.1**	82	54	121	542.88	575.09	170.48	312.44	1046.26	972.96	684.05	1456.09
M03	Chickpea	Lebanon	18406.7	5054.48	5.7	404	3086	87.5	**10.4**	81	54	97	527.28	526.18	116.74	272.82	834.04	856.38	515.81	1333.30
M04	Lentil	Lebanon	22753.5	772.49	15.0	50	158	68.1	**1.3**	1166	546	675	725.38	579.86	132.93	433.90	1364.09	1002.77	879.50	2045.54
M05	Bean	Lebanon	17543.8	1050.10	5.8	174	325	42.8	**12.8**	1166	831	720	704.34	598.09	133.27	496.14	1149.17	1342.61	473.88	1061.50
M06	Bean	Lebanon	22118.7	998.42	4.8	193	366	40.2	**3.6**	100	84	133	818.13	647.94	149.85	406.91	1205.45	1032.75	860.57	1583.56
M07	Lentil	Lebanon	21854.6	750.01	8.2	48	343	51.4	**7.0**	1191	593	739	672.38	676.90	101.54	439.48	1261.86	936.83	613.24	1480.42
M08	Chickpea	Lebanon	17464.1	5256.38	8.7	429	2931	68.3	**1.9**	118	43	79	577.67	572.30	172.29	405.51	1123.50	1429.81	418.15	1175.04
M09	Lentil	Lebanon	22141.5	764.14	12.0	37	168	49.5	**7.6**	1001	456	685	684.11	676.86	87.76	444.90	1386.34	1373.12	672.11	1470.96
M10	Faba	Lebanon	26816.7	1063.16	7.5	84	337	65.5	**5.8**	324	136	524	908.48	909.19	114.91	829.79	1568.78	967.13	570.79	1606.77
M11	Chickpea	Jordan	19127.0	5182.05	7.1	432	3361	76.7	**10.2**	78	42	84	611.38	592.30	160.23	408.83	1164.77	1456.43	452.43	1259.92
M12	Chickpea	Jordan	16016.5	5626.12	5.9	415	2902	78.5	**10.8**	93	51	113	616.15	597.91	128.03	380.57	1081.24	1128.14	419.72	1220.11
M13	Bean	Jordan	18549.6	1434.56	6.8	89	808	71.9	**3.5**	89	72	161	891.38	774.48	118.22	456.23	1347.37	1261.64	536.94	1454.33
M14	Faba	Jordan	25215.5	1151.88	8.1	85	321	40.7	**3.4**	279	105	665	658.32	968.50	121.28	525.16	1587.43	861.29	585.92	1734.41
M15	Chickpea	Syria	21182.5	6194.11	10.7	453	2981	88.1	**8.5**	121	56	107	674.77	700.36	169.48	429.79	1227.73	1190.64	477.89	1354.17
M16	Lentil	Syria	24118.9	849.67	6.2	14	72	36.3	**1.3**	1236	386	923	677.15	671.92	92.51	430.49	1309.39	914.41	614.72	1424.16
M17	Lentil	Syria	26879.0	501.99	5.4	42	138	39.6	**0.4**	886	359	917	651.34	640.46	121.15	418.34	1231.92	1313.03	773.99	1391.08
M18	Lentil	Syria	24977.3	566.91	7.8	27	159	41.8	**0.7**	849	328	917	756.61	744.90	160.61	447.10	1315.34	833.64	789.67	1827.00
M19	Lentil	Syria	25003.6	730.12	8.4	27	110	45.0	**2.6**	924	395	903	760.44	713.90	75.98	439.33	1301.13	1088.44	627.65	1567.18
M20	Chickpea	Syria	21328.3	5907.90	4.2	355	2412	73.6	**10.7**	162	52	82	831.93	582.90	174.56	411.58	1183.04	1502.49	440.01	1224.36
M21	Faba	Syria	29130.9	964.57	4.1	45	218	54.0	**4.2**	951	381	927	607.53	591.38	96.41	301.79	1072.73	721.69	579.15	1519.58
M22	Lentil	Syria	27253.5	941.07	16.7	129	511	77.0	**5.3**	1324	491	903	670.49	706.51	89.89	351.16	1222.38	951.27	930.21	1900.01
M23	Faba	Syria	22933.9	1177.86	5.9	126	502	45.9	**5.4**	1387	566	904	590.72	561.89	94.99	354.72	1048.03	799.61	415.93	1109.96
M24	Lentil	Syria	24337.7	874.10	20.0	88	368	56.5	**4.9**	945	388	906	716.80	717.36	97.65	412.49	1245.14	806.01	780.62	1522.07
M25	Faba	Syria	24002.6	1087.13	7.4	111	487	60.3	**6.3**	881	424	757	628.15	586.60	96.00	319.44	1111.17	752.89	696.78	1593.13
M26	Faba	Syria	28750.8	1046.62	5.1	100	421	46.5	**8.4**	443	434	535	716.15	723.06	112.96	372.56	1354.90	903.96	732.81	1887.56
M27	Lentil	Syria	26642.8	899.16	6.8	42	275	44.9	**3.4**	1143	664	757	687.50	706.61	112.13	336.60	1233.74	916.50	937.50	1964.51
M28	Lentil	Syria	26501.9	745.50	8.5	79	455	56.9	**0.6**	1025	520	754	725.12	712.98	88.57	443.63	1328.88	1011.27	647.51	1505.75
M29	Lentil	Syria	25751.4	638.64	6.1	71	323	47.1	**2.0**	1163	595	754	748.69	740.56	88.73	480.97	1403.30	1092.40	563.67	1526.75
M30	Chickpea	Syria	27724.7	5668.69	5.3	581	4060	73.2	**14.8**	88	138	54	674.98	641.32	185.33	417.70	1246.92	1009.30	741.37	1853.61
M31	Chickpea	Syria	24431.2	5407.52	8.6	564	4049	85.9	**16.3**	88	99	67	539.53	758.57	173.99	437.53	1225.67	992.58	750.90	1832.79
M32	Chickpea	Syria	24189.4	5771.66	8.2	568	4129	58.4	**8.2**	94	98	64	647.30	623.71	165.93	388.61	1088.87	995.26	642.82	1551.96
M33	Lentil	Syria	30894.9	860.96	7.6	82	373	50.3	**5.3**	860	484	753	746.17	708.68	91.21	441.57	1264.45	894.46	1018.63	2347.65
M34	Lentil	Syria	27227.6	725.60	7.5	60	437	74.3	**0.8**	1256	654	753	867.61	819.02	92.54	464.48	1365.71	945.08	960.34	2514.12
M35	Lentil	Syria	29602.0	824.88	9.1	81	459	56.1	**0.5**	875	430	749	767.12	716.27	84.60	432.60	1314.88	706.60	903.56	2066.02
M36	Lentil	Syria	30844.0	670.06	7.6	76	364	24.3	**0.5**	954	346	730	781.98	781.04	101.99	395.45	1313.60	1004.97	930.84	2177.33
M37	Chickpea	Syria	23518.0	5248.19	4.8	417	3030	60.6	**10.4**	77	46	69	689.33	618.16	215.77	408.95	1224.94	984.04	680.52	1737.05
M38	Chickpea	Syria	22806.8	5101.20	4.8	420	3008	67.7	**11.2**	79	57	77	659.82	641.93	165.20	385.78	1192.85	915.15	654.82	1567.14
M39	Chickpea	Syria	21832.2	5914.41	4.8	501	3650	77.4	**12.1**	78	42	80	675.65	712.78	190.01	406.38	1233.20	1341.49	550.77	1607.52
M40	Faba	Egypt	31182.0	1389.59	6.2	159	789	58.5	**6.3**	569	243	616	807.11	786.69	112.30	478.01	1479.85	1086.41	684.66	1956.67
M41	Faba	Egypt	28908.0	1251.91	6.3	137	650	60.1	**5.2**	485	196	530	930.72	870.50	98.93	520.37	1616.15	926.96	1092.60	2333.11
M42	Faba	Egypt	29560.8	1297.32	5.4	132	677	73.0	**5.5**	531	219	578	926.24	867.04	93.39	572.26	1671.65	911.66	886.19	2133.26
M43	Faba	Egypt	27755.3	1256.34	6.8	131	681	69.7	**5.8**	266	196	568	879.62	956.80	178.51	574.98	1732.76	1013.45	998.99	2494.70
M44	Faba	Egypt	37317.0	1035.06	3.5	100	567	102.4	**3.7**	586	237	622	981.72	1025.01	239.60	661.50	1658.74	849.64	896.09	2565.96
M45	Chickpea	Palestina	26834.3	5348.75	5.2	413	2376	44.4	**17.4**	117	46	74	617.68	658.05	175.37	386.47	1163.63	1178.85	1361.54	2138.61
M46	Faba	Palestina	28832.1	1207.83	3.4	110	514	95.6	**8.4**	963	371	659	949.40	633.16	99.68	586.14	1262.13	716.36	915.75	1717.62
M47	Lentil	Palestina	24825.8	945.54	7.9	66	386	74.3	**7.6**	850	395	656	808.21	616.23	102.83	396.60	1002.97	713.66	1244.29	1717.93

Dietary patterns and socioeconomic factors affecting Mediterranean diet adherence in Tunisia

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Abstract

This study aims to assess Tunisian consumers' adherence to the Mediterranean diet (MD) and identify socioeconomic factors influencing this adherence. A national survey involving 600 individuals is performed and data are analyzed. The results of the Mediterranean Diet Adherence Screener (MEDAS) score calculation allowed the classification of consumers into three groups: moderate adherence group (68.7% of the total population), high adherence (5%) and low adherence group (26.3%). The Probit model results showed that individuals with high adherence to the Mediterranean diet primarily consume olive oil, fruits, legumes, and fish and that region is negatively associated with low adherence. In addition, a higher adherence was observed in a higher socio category professional like executive senior. These findings highlight the need for targeted promotion and marketing strategies to raise awareness of the Mediterranean diet's benefits and the health risks associated with modern diets.

Keywords: *Mediterranean Diet (MD), Survey, Adherence, MEDAS score, Qualitative research, Probit model, Tunisia.*

1. Introduction

Over the last few decades, the term "diet" has become extraordinarily popular all over the world. It refers to the style of eating normally adopted by an individual or a community. One of the most famous and widely studied diets is the Mediterranean one. This is a tradition to which the inhabitants and peoples of the Mediterranean basin add or revoke practices, knowledge, products, tastes, appreciations and many other components.

According to study carried out in the 1960s (Cresta *et al*., 1969), Mediterranean diet is characterized by high consumption of cereals, fruit, vegetables, herbal foods and olive oil as the main source of monounsaturated fats and fish, combined with low consumption of potatoes, meat, dairy products, eggs and sweets.

The Mediterranean diet has long been recognized as a healthy dietary pattern associated with numerous health benefits. Several recent epidemiological studies in different countries confirmed

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that adherence to the traditional Mediterranean diet is always linked to a significant reduction in the risk of cardiovascular accidents, the development of certain types of cancer, neurodegenerative diseases such as Parkinson's and type 2 diabetes (Feart *et al*., 2010; Kastorini *et al*., 2011; Kesse-Guyot *et al*., 2012; Martínez-González *et al*., 2008; Angel *et al*., 2009, Vernele *et al*., 2010). However, adherence to this diet can vary considerably from one population to another.

Recently, food consumption was influenced by a number of factors, including availability, climate change, food accessibility, income, socio-economic status, urbanization, globalization and marketing strategies (Kearney, 2010) these changes have led people to move away from the traditional Mediterranean diet, resulting in the emergence of chronic diseases (Sahar *et al*., 2002) and to adopt an unhealthy diet.

In this context, in Tunisia, the consumption pattern has changed in recent years, (following the increase in prices of some products, notably olive oil, Fish and Nuts. Today, Tunisia imports an average of 160,000 tonnes of seed oils a year. The bulk of these are crude soybean and rapeseed oils (80%), considered to be necessities. In terms of value, these imports are estimated at 533 MD in 2022, broken down into 339 MD for imports of subsidized consumer vegetable oils (soybean oils), 95 MD for non-subsidized consumer vegetable oils (corn and sunflower oils) and 98 MD for other types of vegetable oils. (NSI, 2023). This is strongly expected to have influenced Tunisians' eating habits towards olive oil. In addition, according to data from surveys conducted by the National Institute of Statistics, the Average annual consumption per capita (in kilograms) of olive oil decreased from 8.2 kilograms in 2000 to 7.4 kilograms in 2015. This threat is at the root of the increase in diet-related diseases (60% of causes of death): type II diabetes, obesity, and cardiovascular diseases (Sahar *et al*., 2002).

In this context, the study of adherence to the Mediterranean diet proved necessary to understand Tunisian preferences and suggests appropriate policies. This work aims to investigate the level of adherence of the Tunisian consumer to the MD and to identify the socio-economic factors determining this behaviour.

In a first step, the level of adherence to the Mediterranean diet is carried out on the basis of the calculation of the MEDAS score according to its 14 evaluated criteria. Secondly a Probit model is employed to determine the categories of food products that characterize the consumption of the different groups identified according to their level of adherence to the DM. The data used in this work come from a national survey of food consumption according to the Mediterranean diet. Finally, a conclusion is presented, including some policy implications.

2. Methodology

2.1. *Selection of participants and questionnaire design*

The study was carried out by the research team of the Laboratory of Research in Technological Innovation and Food Safety, LR22-AGR01-ESIAT.

A Google Forms questionnaire was distributed to the Tunisian population aged from 18 to 67 through social networks (Facebook) as well as institutional and private mailing lists. Part of the survey was conducted in the field to obtain a more representative and diverse sample. Participation in the study was entirely free, voluntary and anonymous, with participants' providing informed consent for data sharing and privacy policy. No personal data was collected, in compliance with laws on the protection of personal data and the guarantee of digital rights. Consequently, this survey did not require the intervention of an ethics committee.

The first section was dedicated socioeconomic characteristics and anthropometric parameters. the second included questions regarding food consumption based on the PREDIMED method's recommendations, while the third section covered dietary habits.

Weight and height are declared by participants and used to calculate body mass index (BMI), expressed in

$$\frac{weight\ (kg)}{Height\ (m)2}$$

In the second section, to assess adherence to the Mediterranean diet (MedDiet), participants were given a validated 14-item questionnaire (Schröder *et al.*, 2011; Afonso *et al.*, 2014).

The assessment was based on the MEDAS score (Mediterranean Diet Adherence Screener), which was initially developed as part of the PREDIMED (Prevención con Dieta Mediterránea) study designed to evaluate the cardiovascular effects of the Mediterranean diet.

This validated survey consisted of 12 questions on food consumption frequency and 2 questions on eating habits considered characteristic of the Mediterranean diet (Do you use olive oil as the main source of fat for cooking? and Do you prefer eating chicken, turkey, or rabbit instead of beef, pork, hamburgers, or sausages?)

Based on responses to the MEDAS questionnaire, a MEDAS score is calculated, ranging from 0 to 14. Each question received a score of 0 if the condition was not met, or 1 if the condition was met. According to this score, respondents are divided into three categories: (1) low adherence to MD for scores ranging from 0 to 5 (2) medium adherence to DM for scores ranging from 6 to 9, (3) high adherence to DM for scores above 10.

Participants completed the forms directly connected to the Google platform. Once completed, each response was transmitted to this platform and the final database was downloaded as a Microsoft Excel spreadsheet. The questionnaire was disseminated over 3 years from 2021 to 2023.

2.2. *Analysis of adherence to Mediterranean diet*

2.2.1. *Chi-square test*

The Chi-square test is used to test hypotheses to determinate whether data conform to expectations. The basic idea behind the test is to compare the observed values in data with the expected values if the null hypothesis is true. In this study, this test is used to determinate the Percentage of Adherence to the Mediterranean Diet according to Socioeconomic Characteristics.

2.2.2. *Probit model*

Since our explained variable (adherence to the Mediterranean diet) is dichotomous, it requires us to choose an appropriate analysis model. With this in mind, Hurlin (2003) points out that Logit and Probit dichotomous models admit as explained variable, not a quantitative coding associated with the realization of an event (as in the case of linear specification), but the probability of occurrence of this event, conditional on exogenous variables.

The Probit model is a statistical method used in binary classification, which is a type of regression analysis employed to model a binary outcome variable. In the Probit model, the dependent variable is binary, taking on one of two possible values (usually 0 or 1), and the model estimates the probability that the dependent variable is equal to 1 as a function of one or more predictor variables. The dependent variables used are low adherence which takes values of 1 if respondents adhere to a low adherence Mediterranean diet with a score between 0 and 5, and 0 if not. The medium adherence variable takes a value of 1 if respondents adhere to a medium adherence Mediterranean diet, with a score between 6 and 9, and 0 if not. The variable high adherence takes a 1 if participants adhere to a Mediterranean diet with a score above 10.

The independent variables are:

Age, Region, Education level, Socio economic professional, income, olive oil, vegetable, fruit, Meat, Fat, legume, carbonated beverage, Fish and nuts consumption.

*P (Adhérence = 1) = φ (β0 + β1*Age + β2*region + β3*Education level + β4*category + β5* Income + β6*Olive oil + β7*vegetable + β8* Fruit + β9* Meat + β10*Fat + β11*carbonated Beverage + β 12*legume + β13* Fish consumption + β14 Nuts consumption +*

2.3. *Statistical analysis*

Statistical analysis was performed using SPSS (Statistical Package for the Social Sciences) version 11.0. Results are expressed as mean ± standard deviation or frequency (%). the distribution of selected characteristics is compared between groups, using chi-square x2 tests for categorical variables or Student’s t-tests. The significance level was set at 0.05. Probit model and marginal effects were estimated using STATA.

3. Results

3.1. *Characteristics of the participants of study*

A total of 598 participants from different regions in Tunisia (5 respondents were eliminated because they did not indicate their region), aged from 18 to 75, were selected in the survey, including (179) 29.9% men and 70.1% (419) women with an average of 28.8 old. This over-representation of women in the survey population does not necessarily influence the results of the survey, given that in most Tunisian households, women are responsible for errands and purchases. The demographic and anthropometrics characteristics of the persons interviewed showed a normal BMI was found for 48.8% of the survey sample, 4.8% were classified as underweight, 30.8% as overweight, and 15.5% as obese (moderate and severe) (Table 1).

3.2. *Mediterranean diet adherence*

3.2.1. *Calculate score*

26.3% of the total population had low adherence (<5 points) to the MD, while 68.7% had moderate adherence (between 6 and 9 points), and only 5% had high adherence (>10 points) to the MD according to the calculated MEDAS score.

3.2.2. *Factors influencing adherence to the Mediterranean diet*

Results mentioned in Table 2 showed that the older respondents registered the highest adherence to the MD, while adherence was lower among younger participants. The residents of Sehel (Center East) tend to have a higher adherence to the Mediterranean diet 11.5% compared to the residents of the Greater Tunis region which 71.3% follow a diet with moderate adherence. Income is proportional to MD adherence. Most participants with low adherence are from Greater Tunis and the northern region, particularly Bizerte, have a secondary school education level, and earn less than 500 dinars. In contrast, participants earning over 1500 dinars are more likely to adhere to the Mediterranean diet compared to the rest of the participants. Just one par-

Table 1 - Characteristics of the population study. The demographic and anthropometrics characteristics of the subjects who answered the questionnaire.

Sociodemographic Variable	*Percentage % (n)*
Gender	
Men	29.9 (179)
Women	70.1 (419)
Age Group (years)	
18 to 24	25.8 (154)
25 to 30	31.4 (188)
31 to 44	29.9 (179)
45 to 75	12.9 (77)
Adherence score mean	6.6
Mean Age (years)	31.73
Region	
Greater Tunis %	26.8 (160)
North % (Bizerte + other governorates)	36.6 (219)
Sehel: Central East %	16.1 (96)
Central West %	7.9 (47)
South %”	12.7 (76)
Educational Level	
Secondary	8.5 (51)
Higher”	91.5 (547)
Categories	
Student	26.1 (156)
Employee	22.2 (133)
Senior Executive	26.6 (159)
Other (Retired and jobless): Retired = 8%(12), Jobless: 92% (138)	25,1 (150)
Income	
Less than 500 dinars	40 (239)
Between 500 and 1000 dinars	15.4 (92)
Between 1000 and 1500 dinars	20.4 (122)
More than 1500 dinars	24.2 (145)
BMI	
BMI<18.5	4.8 (29)
18,5<BMI<24,9	48.8 (292)
25<BMI <29.9	30.8 (184)
30<BMI<34.9	10.7 (64)
BMI≥35	4.8 (29)

Source: our calculation from SPSS.

Table 2 - Percentage of Adherence to the Mediterranean Diet According to Socioeconomic Characteristics.

	Score d'adhérence		
	≤ 5	*6-9*	*≥10*
All population %	26.3 (157)	68.7 (411)	5 (30)
Gender			
Men	28.5 (51)	64.8 (116)	6.7 (12)
Women	25.3 (106)	70.4 (295)	4.3 (18)
Age %			
18-24 years	35.7 (55)	62.3 (96)	1.9 (3)
25-30 years	29.8 (56)	67 (126)	3.2 (6)
31-44 years	21.2 (38)	72.6 (130)	6.1 (11)
45-75 years	10.4 (8)	76.6 (59)	13 (10)
Region %			
Greater Tunis	26.3 (42)	71.3 (114)	2.5 (4)
North	35.6 (78)	60.7 (133)	3.7 (8)
Sehel: Central East	18.8 (18)	69.8 (67)	11.5 (11)
Central West	12.8 (6)	80.9 (38)	6.4 (3)
South	17.1 (13)	77.6 (59)	5.3 (4)
Educational Level %			
Secondary	45.1 (23)	54.9 (28)	0 (0)
Higher	24.5 (134)	70 (383)	30 (5.5)
Categories %			
Student	26.9 (42)	70.5 (110)	2.6 (4)
Employee	24.8 (33)	70.7 (94)	4.5 (6)
Senior Executive	22 (35)	69.8 (111)	8.2 (13)
Other (Retired and jobless)	31.3 (47)	64 (96)	4.7 (7)
Income %			
Less than 500 dinars	31.8 (76)	64.9 (155)	3.3 (8)
Between 500 and 1000 dinars	30.4 (28)	67.4 (62)	2.2 (2)
Between 1000 and 1500 dinars	22.1 (27)	73 (89)	4.9 (6)
More than 1500 dinars	17.9 (26)	72.4 (105)	9.7 (14)
Class IMC			
BMI<18.5	31 (9)	69 (20)	0 (0)
18,5<BMI<24,9	29.5 (86)	65.8 (192)	4.8 (14)
25<BMI<29.9	22.8 (42)	71.7 (132)	5.4 (10)
30<BMI<34.9	23.4	68.8 (44)	7.8 (5)
BMI ≥ 35	17.2 (5)	79.3 (23)	3.4 (1)

Source: our calculation from SPSS.

ticipant with severe obesity shows adherence to the Mediterranean diet.

3.2.3. *Compliance Test Results for the Mediterranean Diet*

An analysis of the degree of compliance to the MD with each recommendation of the PREDIMED questionnaire was conducted. Table 3 showed a low consumption of olive oil (33%), fruits (18.4%), legumes (27.9%), nuts (12.6%), and fish (7.7%). High consumption of white meat (86.8%), moderate consumption of pasta, rice, vegetables, and other dishes accompanied by sofrito (47%) were observed.

Table 3 - Overall Results Mediterranean Diet Predimed recommendations.

	N	%
1. Using olive oil as the principal source of fat for cooking	439	73.4
2. ≥4 T (1 T¼13.5 g) of olive oil/d (eg, used in frying, slads..)	198	33.1
3. 2 or more servings of vegetables/d	342	57.2
4. 3 or more pieces of fruit/d	110	18.4
5. <1 serving of red meat or sausages/d (1portion =	357	59.7
6. <1 serving of animal fat/d	510	85.3
7. < 3 serving / wk of sweets, commercial cakes	428	71.6
8. ≥7 servings of red wine/wk	-	-
9. ≥3 servings of legumes/wk	167	27.9
10. ≥3 servings of fish/wk	46	**7.7**
11. <1 sweet or carbonated beverages per day?	477	79.8
12. ≥3 servings of nuts/wk	75	12.6
13. Preferring white meat over red meat?	517	86.8
14. ≥2 servings/wk of a dish with a traditional sauce of tomatoes, garlic, onion, leeks sautéed in olive oil	281	47
Mean Score adherence	6.6	

Source: our calculation from SPSS.

3.3. *Food habits*

The study provides key insights into the dietary and lifestyle habits of the surveyed population. 64.9% of respondents are unfamiliar with the Mediterranean diet, highlighting a gap in awareness of this health-promoting eating pattern. Regarding physical activity, 48.3% of the population engages in sports, indicating a moderate level of exercise participation.

Regarding mealtimes, while 4.3% of respondents spend less than 10 minutes eating their meals, the majority (65.1%) take between 10 and 20 minutes. Additionally, 29.6% allocate 20 to 30 minutes to their meals, and only 1% take more than 30 minutes. Dining location preferences reveal that 88.1% of individuals prefer eating at home, whereas only 15.2% choose to dine at restaurants.

Snacking is prevalent, with 63.1% of respondents reporting regular snacking, while 36.9% do not. The consumption of ready-to-eat meals is also notable, with 58% of individuals incorporating them into their diets. Among them, 13.7% consume these meals more than three times a week, reflecting a shift toward ease foods.

Regarding food purchasing decisions, health impact is the most influential factor, considered by 45% of respondents. Price is the second most important factor, influencing 41.1% of consumers, while 40.9% consider nutritional composition as a factor in their decision-making. The least important factor is ease of preparation, suggesting that health and nutrition are prioritized over convenience. Additionally, 39.9% of participants consistently use thyme and spices when preparing meals, reflecting a preference for traditional flavors.

Despite the recognized benefits of Mediterranean products such as olive oil, fish, legumes, vegetables, and fruits, their consumption is hindered by key barriers. The most significant reasons are their limited availability (52.5%) and high cost (46.5%). Addressing these challenges through improved accessibility and affordability could play a crucial role in encouraging healthier eating habits within the population.

3.4. *Probit model: Association socioeconomic factors and food products with Mediterranean diet according PREDIMED*

The accuracy of predictions serves as an indicator of the model's capability to forecast outcomes accurately, and it demonstrates high performance across all three models. Specifically,

Table 4 - Description variables of food consumption by MEDAS.

		N	*%*
Utilization olive oil like principal fat for cooking	Yes	439	73.4
	No	159	26.6
Consumption olive oil (tablespoons) per day	Less than one tablespoon	64	10.7
	1 to 2 tablespoons	172	28.8
	2 to 4 tablespoons	164	27.4
	4 tablespoons or more	198	33.1
Consumption vegetables units per day	0	25	4.2
	1	231	38.6
	2 or more	342	57.2
Consumption Fruits per day	0	30	5
	1	234	39.1
	2	224	37.5
	3 or more	110	18.4
Consumption meat per day	Less than 1	357	59.7
	1 or More	241	40.3
Consumption fat per day (1 unit = 12 g)	Less than 1	510	85.3
	1 or more	88	14.7
Consumption beverages per day	Less than 1	477	79.8
	1 or more	121	20.2
Consumption Legumes per week (1 portion = 150 g)	Less than 2	439	72.1
	3 or more	167	27.9
Consumption fish per week (1 portion = 100-150 g fish)	Less than 2	398	65.1
	2	163	27.3
	3 or more	46	7.7
Consumption sweets	Less than 3	428	71.6
	More than 3	170	28.4
Consumption nuts	Less than 2	390	65.2
	2	133	22.2
	3 or more	75	12.5
Consumption white meat	Yes	517	86.5
	No	81	13.5
Consumption pasta or rice with sofrito	Never	60	10
	1 or 2 times per week	257	43
	2 or more	281	47

Source: our calculation from SPSS.

the correct prediction rate stands at 98.2% for low adherence, 78.2% for moderate adherence, and 94.2% for high adherence.

As shown in Table 10, the LR Chi-square (LR-Chi2) values and their highly significant P-values ($p<0.001$) provide strong evidence for the validity of the Probit model across all adherence levels. These findings suggest that the model reliably captures the variability in adherence levels, providing indirect evidence of its robustness. The bootstrap method was applied to confirm these results and to further test the robustness of the model. The bootstrap analysis validated the consistency and significance of the model coefficients across all adherence categories. The agreement between

Table 5 - Food habits for 598 respondents.

Food Habits		*N*	*%*
Knowledge_ Mediterranean diet	Yes	207	34.6
	No	388	64.9
Physic activity practice	Yes	289	48.3
	No	308	51.5
Snacking	Yes	382	63.9
	No	216	36.1
Place of eating	Home	526	88.1
	Restaurant	91	15.2
Consumption prepared meals	Yes	319	53.3
	No	279	46.7
Times of consumption of prepared meals	0	228	38.1
	1 time	172	28.8
	2 times	90	15.1
	3 times	82	13.7
	4 times or more	26	4.3
Food choices	composition	245	41.1
	price	244	40.9
	preparation	111	18.6
	effect on health	268	45
Time of eating in minutes	less than 10 min	26	4.3
	10 to 20	389	65.1
	20 to 30	177	29.6
	more than 30	6	1

Source: our calculation from SPSS.

the original and bootstrap-estimated results reinforces the reliability of the probit model in explaining adherence behavior. The consistently high and significant LR Chi2 values, together with the validation provided by the bootstrap method, demonstrate the stability and robustness of the model.

Our Probit analysis, exploring influential factors and products related to adherence across low, moderate, and high levels, reveals no noteworthy correlation between age, education level and adherence to the Mediterranean diet.

The Tables 7, 8 and 9 presented the results of Probit estimations on adherence to the Mediterranean diet. Socioeconomic factors had a significant impact on adherence to the Mediterranean diet.

Table 6 - Cultural factors and food consumption (198 respondents added).

		N	*%*
Frequency of consumption of olive oil	sometimes	33	16.7
	rarely	7	3.5
	often	67	33.8
	always	91	46
Consumption of dairy products	never	1	0.5
	sometimes	42	21.2
	rarely	16	8.1
	often	75	37.9
	always	64	32.3
Consumption of fish	sometimes	117	59.1
	rarely	33	16.7
	often	38	19.2
	always	10	5.1
Consumption of fruits and vegetables	sometimes	29	14.6
	rarely	2	1
	often	80	40.4
	always	87	43.9
Using thyme and spices when preparing meals	never	3	1.5
	sometimes	38	19.2
	rarely	12	6.1
	often	66	33.3
	always	79	39.9
Reasons of not consumption Mediterranean products (olive oil, fish, legumes, vegetables and fruit)	availability	104	52.5
	price	92	46.5
	multimedia	6	3
	substitution	37	18.7

Source: our calculation from SPSS.

Region demonstrated a negative effect on low adherence, ($\beta = -0.18$, p-value = 0.008, which explains why residents in the central and southern regions are more likely to adhere to the Mediterranean diet compared to those in the north. The socio-professional Category positively affect-

Table 7 - Results of Probit model in the case of low Adherence.

Variables	*Coefficient*	*Std error*	*Z statistic*	*Sig*	*Interval l95% cl*		*Effet marginal*	*P_value marginal effect*
Intercept: low adherence (cste)	2.007987	.7385652	2.72	0.007	0.5604257	3.455548		
Predictor 1: age	0.0979505	0.1056409	0.93	0.354	-0.1091018	0.3050027	0.0173806	0.353
Predictor 2: region	-0.1617973	0.0606075	-2.67	0.008	-0.2805858	-0.0430087	-0.0287098	0.007
Predictor 3: education level	-0.1479368	0.2645182	-0.56	0.576	-0.666383	0.3705094	-0.0262503	0.576
Predictor 4: categoy	-0.0025022	0.0709116	-0.04	0.972	-0.1414863	0.1364819	-0.000444	0.972
Predictor 5: income	0.0127136	0.0823209	0.15	0.877	-0.1486323	0.1740595	0.0022559	0.877
Predictor 6: cons_olive oil	-0.6482937	0.0837254	-7.74	0.000	-0.8123925	-0.4841949	-0.1150351	0.000
Predictor 7: cons_vegetables	-0.7122491	0.132871	-5.36	0.000	-0.9726714	-0.4518268	-0.1263836	0.000
Predictor 8: cons_fruits	-0.1884572	0.1006616	-1.87	0.061	-0.3857504	0.0088359	-0.0334404	0.059
Predictor 9: cons_meat	0.9344009	0.1581792	5.91	0.000	0.6243753	1.244427	0.1658028	0.000
Predictor 10: cons_fat	1.222604	0.2157803	5.67	0.000	0.7996826	1.645526	0.2169425	0.000
Predictor 11: cons_beverage	0.9240357	0.176815	5.23	0.000	0.5774846	1.270587	0.1639636	0.000
Predictor 12: cons_legumes	-1.332946	0.2195373	-6.07	0.000	-1.763231	-0.9026609	-0.2365219	0.000
Predictor 13: cons_fish	-0.2741812	0.1291255	-2.12	0.034	-0.5272626	-0.0210998	-0.0486515	0.032
Predictor 14: cons_nuts	-.1915687	0.1203207	-1.59	0.111	-0.4273929	0.0442555	-0.0339925	0.110

Source: results from STATA.

ed high adherence (β = 0.44, p-value = 0.046), this suggest that individuals move from lower socio-professional categories (e.g., students) to higher ones (e.g., employees, senior executives), their likelihood of adherence increases.

Consumed food products significantly influenced adherence to the Mediterranean diet.

Olive oil consumption has a positive and significant effect on moderate (β = 0.361, P-value = 0) and high adherence (β = 1.32, p-value = 0.000). Conversely, it has a negative impact on low adherence with β = -0.648, p-value = 0.000 and marginal effect of -0.1151 indicates that increased olive oil consumption lowers the probability of low adherence by 11.51%.

This result demonstrates that olive oil is a key component of the Mediterranean diet. The other products that have a positive and significant effect on moderate adherence are vegetables with a coefficient of 0.374 The products that have a significant negative impact on moderate adherence are meat (β = -0.26, p = 0.029, ME = -0.07), fat (β = -0.546, p = 0.001, ME = -0.16), and carbonated beverages (β = -0.59, p = 0.000, ME = -0.177). These findings explain that individuals with moderate adherence consume more olive oil and vegetables, while reducing their intake of red meat, fat, and carbonated beverages.

For high adherence, we find that olive oil consumption has a significant and positive effect with a high coefficient of 1.32. Additionally, the consumption of fruits, legumes, and fish also has

Table 8 - Results of Probit model in the case of moderate Adherence.

Variables	*Coefficient*	*Std error*	*Z statistic*	*Sig*	*Interval l95% cl*		*Effet marginal*	*P _value marginal effect*
Intercept: moderate adherence (cste)	0.3917553	0.6114361	0.64	0.522	-0.8066375	1.590148		
Predictor 1: age	-.073448	0.0833041	-0.88	0.378	-0.236721	0.0898249	-0.0218584	0.377
Predictor 2: region	.0627457	0.0474431	1.32	0.186	-0.0302411	0.1557325	0.0186733	0.185
Predictor 3: education level	-.0581609	0.2224853	-0.26	0.794	-0.4942241	0.3779023	-0.0173089	0.794
Predictor 4: categoy	-.0406859	0.0569563	-0.71	0.475	-0.1523181	0.0709463	-0.0121083	0.474
Predictor 5: income	-.0159696	0.064966	-0.25	0.806	-0.1433007	0.1113615	-0.0047526	0.806
Predictor 6: cons_olive oil	0.3619611	0.0631213	5.73	0.000	0.2382457	0.4856765	0.1077209	0.000
Predictor 7: cons_vegetables	0.3748955	0.1091703	3.43	0.001	0.1609257	0.5888652	0.1115702	0.000
Predictor 8: cons_fruits	0.0182628	0.0765441	0.24	0.811	-0.1317609	0.1682864	0.0054351	0.811
Predictor 9: cons_meat	-0.2601704	0.1195045	-2.18	0.029	-0.4943949	-0.0259459	-0.0774276	0.028
Predictor 10: cons_fat	-0.5477106	0.1658577	-3.30	0.001	-0.8727856	-0.2226355	-0.1630006	0.001
Predictor 11: cons_beverage	-0.5974356	0.1451423	-4.12	0.000	-0.8819092	-0.3129619	-0.1777989	0.000
Predictor 12: cons_legumes	0.202791	0.1342068	1.51	0.131	-0.0602494	0.4658315	0.0603513	0.131
Predictor 13: cons_fish	-0.0871756	0.0931067	-0.94	0.349	-0.2696614	0.0953103	-0.0259438	0.348
Predictor 14: cons_nuts	-0.0091607	0.0862765	-0.11	0.915	-0.1782596	0.1599381	-0.0027263	0.915

Source: results from STATA.

a significant positive effect on high adherence. Red meat has a negative effect on high adherence to the Mediterranean diet. Olive oil, fruits, legumes, and fish characterize the diet of Tunisians who exhibit high adherence.

For low adherence, the consumption of olive oil, vegetables, fruits, legumes and fish has a significant negative effect.

The consumption of red meat, fats and carbonated beverages has a positive effect on low adherence. Participants showing low adherence tended to consume red meat, fats, carbonated drinks, and sweets, while avoided consuming olive oil, vegetables, fruits, legumes, fish, and nuts.

4. Discussion

Our research emphasized the significance of the Mediterranean diet, a culinary heritage shared by Tunisia and other Mediterranean nations, which is gradually fading in favor of a more contemporary dietary regimen. The present study described the patterns of the MD in a sample survey of adult Tunisian population and its association with socioeconomic factors using the MEDAS screener and the Probit model. This method has been recently validated as a reliable tool for assessing adherence to the Mediterranean diet across various countries in the Mediterranean regio (García-Conesa, 2020; Címtia

Table 9 - Results of probit model in the case of high adherence.

Variables	*Coefficient*	*Std error*	*Z statistic*	*Sig*	*Interval l95% cl*		*Effet marginal*	*P _value marginal effect*
Intercept: high adherence (cste)	-12.78445	2.936294	-4.35	0.000	-18.53948	-7.029419		
Predictor 1: age	-.223026	.2665797	-0.84	0.403	-.7455126	.2994606	-.0152156	0.401
Predictor 2: region	.21312	.1583303	1.35	0.178	-.0972016	.5234417	.0145398	0.170
Predictor 3: education level	0	(omitted)					0	
Predictor 4: categoy csp	0.4471832	.2242672	1.99	0.046	.0076277	.8867388	.0305084	0.040
Predictor 5: income	0.5131645	.2104712	0.54	0.049	-.2993515	.5256806	.0077205	0.591
Predictor 6: cons_olive oil	1.325415	.3433408	3.86	0.000	.6524793	1.99835	.0904243	0.000
Predictor 7: cons_vegetables	0	(omitted)					0	
Predictor 8: cons_fruits	0.9482344	.2764718	3.43	0.001	.4063596	1.490109	.0646918	0.000
Predictor 9: cons_meat	-1.803861	.4621507	-3.90	0.000	-2.70966	-.8980626	-.1230655	0.000
Predictor 10: cons_fat	0	(omitted)					0	
Predictor 11: cons_beverage	-1.554809	1.202846	-1.29	0.196	-3.912344	.8027265	-.1060743	0.192
Predictor 12: cons_legumes	2.537323	.5267845	4.82	0.000	1.504844	3.569802	.1731047	0.000
Predictor 13: cons_fish	1.402682	.3273239	4.29	0.000	.7611391	2.044225	.0956957	0.000
Predictor 14: cons_nuts	.1863832	.2128783	0.88	0.381	-.2308507	.6036171	.0127157	0.380

Source: results from STATA.

Ferreira-Pêgo *et al*., 2019; Hidalgo Mora, 2020). Among the various adherence scores developed, the 14-item MEDAS screening tool, initially validated for the Spanish population in the PREDIMED study (Schröder *et al*., 2011), has been widely studied for its applicability in several countries worldwide (Hebestreit *et al*., 2017; Bottcher *et al*., 2018; Papadaki *et al*., 2018; Know *et al*., 2020). The PREDIMED score derived from the MEDAS differs slightly from those used in other studies. It establishes specific cutoff points for the intake of key Mediterranean diet components, such as nuts, legumes, and olive oil, while also considering the consumption of non-traditional Mediterranean foods, including sugary soft drinks and pastries (Schröder *et al*., 2011). The use of MEDAS in research in Tunisia is not yet widely adopted, and this method is among the first applications of its kind in this study. One of the limitations attributed to the 14-MEDAS is that, in most studies, this score was validated for a specific sample population (i.e., individuals aged 55 to 80 years at high risk of coronary heart disease), meaning the results cannot be generalized to the broader population. However, the validity of the 14-MEDAS has also been analyzed in other studies, such as the one by García-Conesa *et al*. (2020), which assessed it in a general adult population (>18 years old) across various Southern European countries. In our study, the 14-MEDAS questionnaire is also used for a general adult population, without specific age restrictions, there by broadening the scope of the results and providing a better understanding of Mediterranean diet adherence in a more general context. Another limitation is that the MEDAS primarily focuses on specific components of the diet. For this reason, we have integrated questions regarding dietary factors and eating habits to obtain a more comprehensive assessment of Mediterranean diet adherence, as well as the impact of socio-economic, cultural factors, and eating behaviors.

The results of MEDAS showed that the majority of the participants have a moderate adherence to traditional Med Diet. Approximately 26.3% of the total population exhibited poor adherence to the Mediterranean diet, scoring at least 5 points on the 14-point questionnaire, while 68.7% displayed moderate adherence, and only 5% had high adherence, scoring 10 points or more**.**

In the Probit model findings, high adherence to the MD is characterized by high intake of fruits, fish, olive oil and legumes according to the MD score, and by the absence of meat consumption. The parametric terms found to be significant predictors of moderate adherence in this study were olive oil consumption and vegetable consumption with positive effect, meat consumption, fat intake, and the consumption of carbonated beverages with negative effect.

Among the factors and products influencing positively the probability of having a low score of adherence to MD were meat consumption, fat consumption and carbonated beverage. Region, olive oil consumption, vegetable consumption, fruit consumption, legume consumption fish consumption had a significantly negative impact on low adherence.

Results showed that high adherence rate was observed among participants, primarily concentrated in the Central East Sehel governorate and that the majority of adherents to the mediterranean diet in this region are aged between 45 and 75, with a university education, holding senior positions, and earning an income exceeding 1500 dinars. This can be explained by the fact that this region is renowned for its high production of seafood and olive oil. (Arfaoui *et al*., 2022).

Olive oil consumption in the Center-East region was the highest compared to other regions, with an average of 12.6 kg per capita per year, compared to the national average of 7.4 kg per capita in 2015 (NSI). This disparities between coastal and continental Tunisian inhabitants of fish and sea food consumption depending on the availability and supply of fish products, consumption habits and product quality are proven by the finding of Dhehibi *et al*., 2005. The average fish consumption in the Center-East region is 16.5 kg per capita per year, compared to a national average of 9.3 kg per capita per year, according to the Tunisian statistics of the National Institute of Statistics in 2015 and that older individuals maintain loyalty to traditional lifestyles and dietary habits acquired during their upbringing, leading them to eschew modern dishes and fast foods also taking into account that the majority are farmers of these products. This shift is characterized by a decreased intake of essential MD foods like fruits, vegetables, and legumes, coupled with an increased consumption of fats and proteins (Naska and Trichopoulou, 2014; Sahingoz and Sanlier, 2011). Similarto the Casa Blanca (Mohtadi *et al*., 2020) study and the work of El Rhazi and colleagues (El Rhazi *et al*., 2012). However, they examined sociodemographic factors related to Mediterranean diet adherence in a Moroccan population and found no correlation between age and adherence to the Mediterranean diet.

In the other hand, it has been reported that age was predictive factor of MD adherence in most Mediterranean regions as in Spain (Arcila-Agudelo *et al*., 2019; Buckland *et al*., 2011), Italy (Grosso *et al*., 2013), and Greece (Kontogianni *et al*., 2008; Kyriacou *et al*., 2015), it is believed that younger people are more likely to adopt western dietary patterns.

It should be also taken into account the effect of advertising and the media, and the promotion of industrialized, sweetened products, more than fresh produce, since the latter do not generally belong to recognized brands and are not widely available in supermarkets.

The bootstrap method was used, a widely recognised resampling technique, to ensure the reliability of our results. This approach involves generating multiple random samples with replacement from the original data set, recalculating the probit model coefficients for each sample, and deriving robust confidence intervals. The bootstrap method is particularly advantageous as it does not rely on strong parametric assumptions about the error distribution or explanatory variables, making it well suited to complex data structures. Our results showed consistent coefficients and significance levels across bootstrap iterations, confirming the robustness and stability of the estimates.

Results of Probit model confirmed that residents who tend to adhere to the Mediterranean diet consume olive oil, fish, fruits and legumes at a high frequency. These foods are fundamental components of traditional Tunisian cuisine, reflecting a dietary pattern rich in healthy fats, high-quality proteins, and essential nutrients. This finding improve the importance of following traditional Tunisian eating habits which present a strong case for encouraging their adoption as part of a balanced and sustainable diet. Residents of the central, western, and southern regions are those most attached to their culinary traditions. This can be attributed to the fact that the lifestyle in these areas has not been as heavily influenced by urbanization compared to the northern regions and Greater Tunis. According to the results of the Probit model, residents of the north and Greater Tunis tend to have lower adherence to the Mediterranean diet. They consume more meat, fats, carbonated beverages, and sweets. This is due to the lack of time for cooking, especially because of women's work, and the availability of processed foods. The residents of the center west and south represent the highest percentage of those with moderate adherence to the Mediterranean diet. The people in these regions are attached to their culinary traditions, but their issue lies in the high consumption of meat, due to the limited availability of fish in these areas. The Central West, Southwest, and Northwest regions recorded the lowest average fish consumption, with an average intake of less than 4 kg per person per year (NSI, 2015). These differences between regions influence the eating habits in each region. Improving the availability of high-quality fish could boost consumption in these regions. Promoting better packaging and transportation methods would ensure a consistent supply of fish to interior regions. Given the importance of fish in the Mediterranean diet, these measures are essential for maintaining a healthy and balanced diet in these regions. (Barhoumi *et al*., 2024).

Tunisia is in the early stages of a nutritional transition, where traditional dietary practices remain prominent but are starting to be influenced by Western food patterns, particularly among the younger population. In addition, no significant differences in MD adherence according to education level because the majority of participants have a university education level. In fact, the interviewees who showed a high level of adherence represent different educational levels, this is explained by the fact that the respondent could be a manufacturer of the product in concern or have a high income (trader, farmer) without necessarily having a university level of education, or it could also depend on family habits where pupils and children will adhere or not to the MD.

The dependence of income on adherence to Mediterranean Diet could suggest that the cost of Mediterranean products acts as a barrier for individuals with lower incomes in adopting the Mediterranean diet compared to those with higher incomes. Indeed, Tunisia has opted to import seed oils in order to release larger quantities of HO for export, needed to increase foreign exchange earnings and meet the needs of a growing population. This policy has had a significant impact on olive oil cost and the structure of edible oil consumption, which is now dominated by seed oils (72% of total oil demand), compared with 28% for olive oil, which was the main oil consumed in 1970. This explain lower adherence to the Mediterranean diet among people with low and middle incomes according to the National Observatory of Agriculture (NOA). In the other hand, fish consumption has risen significantly, climbing from 6.1 kg to 9.3 kg per capita annually between 1985 and 2015 (NSI., 2015). Despite this overall growth, there exists a pronounced disparity in consumption patterns between coastal and inland regions highlighting the influence of geographical factors on dietary habits (Barhoumi *et al*., 2024). The residents of the Central-East region show the highest adherence to the Mediterranean diet, which is not influenced by the high prices of Mediterranean diet products such as fish and olive oil. This is primarily due to the availability of these products, as the region is a major producer of both. Additionally, most of the population in this area consists of farmers and fishermen, and their food culture places great importance on these products. In addition, Senior executives show the highest adherence to the Mediterranean diet. This socio-professional category benefits from financial independence, a high income, and a high level of education, along with greater awareness of the health benefits of the Mediterranean diet. All these factors contribute to encouraging them to adopt healthy eating habits.

These results tend to be in line with some studies that have shown like González and colleagues (Gonzalez *et al*., 2002) who concluded that Mediterranean diet adherence in Spain was lower in young individuals those with higher incomes and in females. The same results were found in other Mediterranean countries (Katsarou *et al*., 2010; Panagiotakos *et al*., 2008).

Overall results on the Mediterranean diet adherence test showed a preference for white meat consumption: 84.8% of the population prefers white meat, high consumption of animal fat, sweets, a moderate consumption of pasta, rice, and vegetables, a low consumption of fruits, nuts, legumes and fish. These results similar to this study realized by Aounallah-Skhiri *et al*., 2011. Since the 1980s, the Tunisian government has actively promoted the production of poultry and similar products as part of a strategic effort to enhance food security and meet growing demand. This initiative led to a significant boost in poultry production, which was further amplified by a shift in consumption patterns following the 2011 revolution. With the rising cost of red meat, poultry emerged as a recommended alternative by nutritionists and a direct substitute for red meat in the Tunisian diet (Boudiche *et al*., 2022). As a result, per capita poultry consumption increased from 5.3 kg to 20.6 kg per year between 1985 and 2015, while beef consumption dropped from 7.6 kg to 4.9 kg in the same period (NSI, 2015).

Furthermore, adherence and BMI are inversely proportional, this is explained by the fact that the Mediterranean diet does not include high-calorie foods, and this has been shown by several research. A study conducted by Damigou *et al*. in 2022 assessed changes in adherence to the Mediterranean-type diet (MTD) and their impact on body weight over a 20-year follow-up period. The findings revealed an inverse relationship between MTD adherence, changes in adherence, and both BMI at 20 years and the average BMI during the follow-up. Maintaining consistent adherence to MTD over the 20-year period was linked to a more than 90% reduction in the risk of sustaining overweight or obesity. The Mediterranean dietary pattern contributes to obesity prevention and weight management through several key components. These include the high polyphenol content found in extra virgin olive oil (EVOO), fruits, vegetables, herbs, spices, whole grains, legumes, and nuts.

Despite the widely touted health benefits of the Mediterranean diet and its rich cultural heritage, Mediterranean populations, particularly the younger generations, have been gradually moving away from this traditional dietary pattern over the past few decades. Factors such as urbanization, population growth, and the increasing globalization of the food supply have been identified as potential causes for this shift (Vernele *et al*., 2010). It is crucial to raise awareness among the youth and encourage them to enhance their eating habits, as dietary behaviors are established early in life and significantly impact the quality of life in adulthood. Early interventions of this nature can play a substantial role in preventing chronic diseases and fostering sustainable lifestyle habits rooted in balanced nutrition and regular physical activity (Hachem *et al*., 2016).

Paradoxically, while the Mediterranean diet is gaining global popularity and receiving increasing recognition from the international scientific community, Studies have shown a decline in this dietery model across various regions of the Mediterranean (Lacirignola and Capone, 2009; Naja *et al*., 2021). Dernini and Capone (2021) called for the revitalization of the Mediterranean diet by enhancing its current perception, particularly among the younger generation, not just as a healthy diet but also as a model for a sustainable lifestyle.

In this context, the studies conducted by Capone *et al*. (2021) and Ridolfi *et al.* (2020) provide an in-depth analysis of the challenges and perspectives of food systems in the region, further highlighting this trend. These works highlight the importance of collaboration between the Mediterranean sustainable food systems (SFS-Med) Platform, developed by CIHEAM, FAO, and the Union for the Mediterranean (UfM) to promote the transition of food systems towards sustainability and accelerate the achievement of the Sustainable Development Goals (SDGs) in the region. The platform provides a unique opportunity to unite various technical, scientific, and political mandates, fostering stronger partnerships aimed at creating more resilient and sustainable food systems in the Mediterranean.

The promotion of the Mediterranean diet, recognized globally as a model of sustainable diets, represents a concrete step in advancing sustainability in the region. The unsustainability of food systems within the Mediterranean is contributing to the erosion of the cultural food heritage, represented by the Mediterranean diet. Furthermore, transforming food systems in the Mediterranean necessitates the formation of multi-stakeholder partnerships, with collaboration between intergovernmental organizations, governments, academia, the private sector, and civil society. In light of the heterogeneity of food systems across Mediterranean countries, adopting a context-specific yet integrated approach is critical to gain a holistic understanding of food systems. This approach should focus on addressing all components within the entire food system, rather than viewing them separately, to assess their impacts and trade-offs comprehensively. Transitioning towards sustainable food systems involves addressing issues in the consumption side of the food chain while considering the connections between production and consumption. Therefore, a comprehensive strategy is essential to ensure that all stages of the food system are aligned to promote sustainability (Capone *et al*., 2021). The authors highlight the need to better understand food-related choices and the drivers behind them in relation to their cultural, social, economic, and environmental circumstances (Ridolfi *et al*., 2020).

Establishing a greener, bluer, and more circular economy are three key concepts of the SFS Med food systems transformation aimed at promoting sustainable development and improving the quality of life for the population. It is crucial to support the position of farmers and fishers within the value chain, promote "green" and "blue" growth, foster a circular economy, and encourage sustainable food consumption while ensuring access to healthy and affordable food for everyone (Ridolfi *et al*., 2020).

This study focused on quantitative methods, specifically the probit model and the chi-square test, to identify statistical associations between dietary habits and socio-demographic factors in Tunisia. These methods allowed us to analyse broad patterns and associations at the population level. However, it's recognized that a qualitative approach, such as in-depth interviews or focus groups, could provide deeper insights into the motivations, cultural influences and individual perceptions behind the dietary behaviors observed. While our research was designed to provide a quantitative overview of dietary patterns, future studies could benefit from integrating qualitative methods to explore the underlying reasons for certain dietary choices, the role of social norms and personal experiences that influence adherence to diets such as the Mediterranean diet.

5. Conclusion

In conclusion, two-thirds of the Tunisian population show moderate adherence to the Mediterranean diet, while only 5% exhibit high adherence. This highlights a significant deviation from the traditional Tunisian dietary pattern associated with the Mediterranean diet. There is a notable shift away from the characteristic consumption model of the Mediterranean diet in Tunisia.

Studying the factors influencing adherence to the Mediterranean Diet in Tunisia socio-professional category (SPC), and region have proven to be determining factors of the Tunisian behavior consumer. The lifestyle, particularly in the capital, and low purchasing power have negatively impacted adherence to the Mediterranean diet. While Tunisia has successfully controlled communicable diseases, the prevalence of food-related chronic diseases is on the rise, accounting for 60% of deaths. Obesity now affects half of the population, with 33.7% classified as overweight and 26.2% as obese (Ministry of Health, 2019; Dogui *et al*., 2021), which is double the global average of 11.7% (FAO, 2014). Additionally, the high prevalence of diabetes underscores a growing public health concern, with around 15.1% of the adult population currently affected, according to the latest national health statistics. This rising prevalence of chronic diseases is strongly associated with shifts in dietary habits, marked by a move away from traditional diets toward more processed and high-calorie foods. To encourage healthier eating habits, it is essential to offer breakfast options that are not only nutritious but also convenient and easy to prepare. A Mediterranean diet-inspired breakfast, rich in essential nutrients like healthy fats, fiber, and protein, can be a practical solution. For instance, incorporating nuts, Greek yogurt, and fresh fruits create a balanced breakfast.

The increase of the agri-food industry, with its growing supply of industrialized foods and ready-made meals, are causing the decline in traditional mediterranean diet style. This shift towards processed and ultraprocessed products is partly replacing the consumption of fresh, whole foods that are central to the Mediterranean diet, including fruits, vegetables, legumes, whole grains, and healthy fats such as olive oil and nuts.

Increases in the prices of cereals, fish and fruit, and fluctuating olive oil prices, which are essential components of the Mediterranean diet, have the potential to influence food choices and adherence to the Mediterranean diet in Tunisia. Agricultural policies play a crucial role in mitigating the effects of these price rises, in particular by ensuring that Mediterranean staple foods remain affordable and accessible. While these price changes reflect broader global trends, they also underline that a dynamic and transparent agricultural policy that adapts to international changes and includes all categories of farmers is crucial to ensuring sustainable agricultural development and food security in Tunisia, focusing on local production to reduce import dependency and ensure the sustainability of key Mediterranean foods (Thabet *et al.*, 2024).

On a practical level, marketing campaigns to raise consumer awareness of the benefits of the main staples of the Mediterranean diet could be a solution to improve adherence to this regime. On a national level, subsidizing olive oil could minimize the consumption of vegetable oils and reduce the cost of olive oil. It would also be advisable to organize supply chains between regions to balance consumption somewhat better.

Additionally, this work could be supplemented by surveys by periods of time (summer/winter), or 5 years ago and the current year to highlight the evolution of consumption over time.

A more in-depth study could be carried out to better understand the reasons for consumer choice, for example conducting a survey of farmers and non-farmers, or in urban and rural regions.

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Tracing the root of the evil in the carbon footprint of tomato production: Implications for optimization process and policy formulation

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Abstract

While agriculture's role in carbon emissions has been studied broadly, there is a notable lack of disaggregated studies that focus on the carbon footprint of specific products, such as tomatoes. This is further exacerbated by the fact that tomatoes are a staple food in many countries, and the carbon emissions associated with their production could vary significantly across different cultivation methods, regions, and supply chains. This literature gap limits our understanding of where emissions originate and where they can be mitigated. In this context, the aim of the present paper is to provide a comprehensive evaluation of the equivalent carbon footprint in greenhouse tomato production in Greece by means of a Life Cycle Assessment. Results indicate that the energy required to produce the tomato is the factor that has the greatest impact on the environmental impact. The fertilizers and the materials used to package the product also affect significantly the overall environmental impact. Tomatoes are an essential component of global food systems. Thus, even marginal improvements in the carbon efficiency of tomato production could yield significant environmental benefits, and a detailed carbon footprint analysis could influence policy and practice.

Keywords: *Carbon footprint, Life Cycle Assessment (LCA), Sustainable tomato production, Optimization process, Agricultural policy.*

1. Introduction

Agriculture is a major contributor to the global carbon footprint, with its activities accounting for roughly a quarter of global greenhouse gas emissions (Poore and Nemecek, 2018; Lynch *et al*., 2021). The sector plays a pivotal role in shaping environmental sustainability. Among many different agricultural crops, tomato (*Solanum lycopersicum L.*) holds a place of significant importance, ranking as one of the most cultivated and consumed vegetables worldwide, second only to the potato in terms of production volume (Padmanabhan *et al*., 2016).

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Tomatoes, a staple food in global diets and one of the most widely cultivated crops worldwide, are grown in over 180 countries and account for around 182 million tons of production annually (FAOSTAT, 2022). In 2022, the European Union produced a significant quantity of tomatoes, with Italy being the largest producer, accounting for 40% of the total EU production. Spain and Portugal followed, producing 24% and 9%, respectively. Overall, the EU harvested around 15.4 million tons of tomatoes in 2022 (European Commission, 2022).

In Greece, tomato production is a significant agricultural industry, with the country consistently ranking among the top 20 tomato producers worldwide. Within Europe, Greece often ranks among the top five tomato-producing nations, depending on the year (FAOSTAT, 2022. Greece is also a significant producer of tomatoes within the Mediterranean region, particularly known for its greenhouse cultivation methods. In terms of production volume, Greece consistently produces over 900,000 tons of tomatoes annually (FAOSTAT, 2022).

While precise statistics on tomato production's standalone carbon footprint are not always available, since its carbon emissions could vary significantly across different cultivation methods, regions, and supply chains, it is evident that reducing emissions in such high-produced crops could have a meaningful impact on global efforts to decarbonize agriculture. Decarbonizing major agricultural industries, such as the tomato industry, is key to tackling climate change (Ardakani *et al*., 2019; Migliore *et al*., 2019; Sovacool *et al*., 2021), but to do so we need reliable ways to measure the carbon footprint of goods produced in this industry. Carbon footprint assessments help identify the most significant sources of emissions within production processes, allowing for targeted mitigation strategies.

The production of tomatoes involves a variety of processes, including land preparation, cultivation, irrigation, fertilization, harvest, post-harvest processing, packaging, and transportation (Khoshnevisan *et al*., 2014). These stages contribute to carbon emissions through energy use, material inputs (such as fertilizers, pesticides, and packaging), and waste generation. Given the complexity of production systems and the broad scope of the topic, there is a pressing need to study the environmental impact of tomato production at various stages of the production process. Such understanding is essential for developing more eco-friendly agricultural practices and informed policies that mitigate carbon emissions effectively. Without a clear understanding of where environmental issues in tomato production stem from, it becomes impossible to implement the right strategies for mitigation. As tomatoes are a staple food in numerous countries and a key element in global food systems, even marginal improvements in the carbon efficiency of their production could yield substantial environmental benefits.

To this end, the overarching scope of the present study is to evaluate the carbon footprint associated with tomato production in Greece, with a focus on the equivalent carbon dioxide (CO_2) emissions resulting from both the materials and processes involved in cultivation and the management of waste post-production. Specifically, the study quantifies the total CO_2 emissions of tomatoes by means of a Life Cycle Assessment (LCA), considering key factors such as energy use, fertilizers, packaging, and waste management practices. By identifying major contributors to the carbon footprint and exploring strategies for mitigation, this research seeks to provide valuable insights into how the tomato production process can be made more sustainable.

The subsequent sections are organized as follows: The next section briefly outlines the relevant literature. The third section describes the LCA methodology and the utilized data inventory. The fourth section presents the results and discusses the findings. The last section concludes and also examines the implications of these results for practice and policymaking.

2. Literature Review

The environmental impacts of agricultural practices have garnered significant attention in recent years (Springmann *et al*., 2018). Several studies have focused on evaluating the carbon footprint associated with these practices, emphasizing the need for sustainable production methods to mitigate greenhouse gas (GHG) emissions (González-García *et al*., 2018; Poore and Nemecek, 2018; Castillo-González *et al*., 2024). And if, as alleged, agriculture's role in carbon emissions has been studied broadly, there is a notable lack of detailed research specifically addressing the carbon footprint of tomato production (Bosona and Gebresenbet, 2018; Canaj *et al*., 2019).

A comprehensive study by Solimene *et al*. (2023) explores the carbon footprint of tomato cultivation using Life Cycle Assessment (LCA). The article discusses the various methodologies employed to assess the carbon footprint and highlights the role of innovative farming techniques, such as precision agriculture, in minimizing environmental impacts. Interestingly, their findings indicate that the largest contribution to climate-changing gases comes from the use of fertilizers. The authors advocate for policies that encourage sustainable agricultural practices to ensure long-term environmental health and food security (Solimene *et al*., 2023).

Pedala *et al*. (2023) present a detailed evaluation of the environmental impacts of agriponic systems, with a specific focus on tomatoes. Their findings suggest that the carbon footprint of tomato production varies significantly depending on regional practices and technologies employed. The study emphasizes the interconnectedness of food production systems and their contribution to climate change, advocating for a holistic approach to sustainability that includes reducing emissions throughout the supply chain. The authors call for further research to explore alternative materials used for seed pods, fertilizer bottles, and greenhouse components, in order to reduce the reliance on plastic, concluding that utilizing materials that have lower environmental impacts, or are made from recycled plastics can be beneficial. This study advocates comprehensive strategies addressing both primary production and supporting materials, suggesting the potential of locally tailored approaches in regions where traditional and modern agricultural practices coexist. Common pattern in Mediterranean countries.

The research conducted by Bosona and Gebresenbet (2018) highlights the importance of using lifecycle approaches to mitigate the environmental impact of tomato production. Particularly, their empirical effort attempts to assess the environmental burdens of organic tomato produced and distributed in Sweden. The study reveals that even though the drying process consumes additional energy, it can be traded off by reduction of product volume and packaging material, which in turn reduces transport fuel and post-harvest product loss, especially in the case of transporting over long distances. Moreover, in the detailed study of Del Borghi *et al*. (2014), the results of a Life Cycle Assessment (LCA) performed on 13 tomato-based products produced in Italy are presented and discussed. Findings indicate that the agricultural phase and packaging production are the life-cycle stages with the highest impact in all the categories considered. The authors conclude that the identified improvement options related to the packaging subsystem are the reduction of weight and the switch to different packaging materials. These studies underscore the need to evaluate both packaging and transport in carbon footprint assessments for tomatoes, which could be particularly relevant in Greece, where exports and long-distance transport are common.

A recent study conducted by Naseer *et al*. (2022) explores the environmental impact of tomato production, focusing on quantifying and mitigating the carbon footprint across different production systems. The study identifies energy-efficient practices and optimized resource use as critical strategies for reducing emissions. Findings underscore the need for adopting renewable energy sources and precision agriculture techniques, especially in greenhouse systems, to lower the carbon footprint in tomato cultivation sustainably. These findings align with the need for region-specific solutions in Mediterranean climates, where solar energy and optimized irrigation may offer viable alternatives to more energy-intensive systems.

Lastly, it is well-documented in the relevant literature that LCA studies can capture the environmental impacts of foods, diets, and food production systems (Ruviaro *et al*., 2013; Dias *et al*., 2017; Sala *et al*., 2019; Pazmiño and Ramirez, 2021; Pedala *et al*., 2023; Kumar *et al*., 2024; Lee *et al*., 2024). Life Cycle Assessment (LCA) is a key methodological reference for identifying and addressing the above-mentioned issues. It is widely applied across various sectors, including food production, despite the inherent complexity of such processes (ISO 14040:2006a; ISO 14044:2006b). The principles of LCA allow the assessment of the global extent of the inputs, outputs, and potential environmental impacts throughout the life cycle of a product system. LCA follows the phases of (1) goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation (Cucurachi *et al*., 2019).

The relevant literature reveals a clear consensus on the significant environmental impacts of tomato production, particularly concerning carbon emissions. The adoption of sustainable practices, supported by comprehensive assessments and targeted policies, is crucial for reducing the carbon footprint and promoting environmental sustainability in the agricultural sector. However, the aforementioned urge the need for continuous research for national and regional adaptations to enhance the sustainability of tomato production. By analyzing the carbon footprint of tomato production in Greece, we can contribute to the EU's broader agenda on climate change and sustainability. This can also serve as a model for similar studies in other Mediterranean countries and provide benchmarks for other regions in Greece or the EU to assess their own agricultural sustainability initiatives.

3. Methodology and Data

3.1. *Methodological Framework*

The stages of the Life Cycle Assessment (LCA) methodology used for the evaluation of equivalent carbon footprint (CO_2) for the production of tomatoes are briefly described as follows:

a) Goal and scope definition. It is the first stage of the methodology, where certain theoretical parameters that characterize the study are determined. These parameters include the objective of the study, its scope, the definition of the system being studied and the boundaries of that system, as well as the geographical coverage and the functional unit used in the study.
b) The Life Cycle Inventory (LCI) stage requires a detailed recording of all materials (including energy) and processes consumed and performed, respectively, throughout the production of the tomatoes (from the acquisition of the raw materials in the production to the packaging and management of the resulting waste).
c) In the Life Cycle Impact Assessment (LCIA) stage, the results of the assessment of the environmental impacts caused by tomato production in terms of equivalent carbon footprint (CO_2) are obtained.
d) The last stage is the interpretation of results. The results of the environmental impact assessment are summarized and are used to draw conclusions based on the objective of the study that has been determined. The present analysis refers to the environmental aspects of the tomato production process without considering economic or social factors.

3.2. *Goal and Scope Definition*

The objective of the present study is to evaluate the environmental impacts caused by the production of tomatoes by means of the valuation method regarding the equivalent carbon footprint (CO_2) that is produced. The results can be used to shape the environmental profile of the product under consideration for its environmental certification as well as to determine the impact of the materials consumed and the processes followed for its production on the environment.

The boundaries of the system that are examined from "a set of criteria that determine which individual processes are part of the system" (ISO 14040, 2006a). For this study, the boundaries of the system cover the entire production process of the tomato product, from the stage of obtaining the raw materials required, the materials and energy consumed, and the production processes up to the stage of packaging the tomatoes and the management of the resulting waste.

As far as the process of allocation is concerned, it is defined according to ISO 14040 (2006a, b) as "the separation of inputs and outputs referred to a process or system between the system under study and another system or systems". In the frame of the present study, there is only the production of tomatoes, and hence, there is no need for any separation.

According to ISO 14040 (2006a, b), the functional unit describes "the basic operation of a system and provides a reference against where input and output data can be quantified". For the present study, the functional unit used is one kilogram (1 kg) of finished tomato product, while the geographical coverage refers to Greece and the wider European area.

3.3. *Life Cycle Inventory*

This section outlines the materials and products consumed during tomato production, along with the procedures followed throughout the process. It also records all waste materials generated after production and their respective management methods. The data for greenhouse tomato production were obtained from a typical greenhouse production company in Northern Greece, and particularly, from the region of Eastern Macedonia and Thrace (NUTSII). The area is dominated by heated greenhouses for tomato production. This reliance of the area on greenhouse-based production provides an opportunity to analyze energy consumption and greenhouse gas emissions associated with controlled-environment agriculture. The production takes place annually, from March to November, yielding a total of 7,500 tons (t) of tomatoes per growing season. The quantities mentioned below correspond to one full growing season and are subsequently adjusted to the functional unit of this study, which is 1 kilogram (kg) of the final tomato product. Particularly:

I. Energy

The amount of energy consumed during tomato production is recorded. This energy concerns the electricity consumed during production, which comes from the public electricity supply network in Greece. At the same time, the company uses a high efficiency cogeneration (CHP) of electricity and heat systems with generators of electricity-heat-CO_2 with a total capacity of 8 Mw, which consume natural gas. The thermal energy and carbon dioxide (CO_2) emissions produced by the cogeneration system are used during the tomato production process, avoiding the use of an additional source of thermal energy and carbon dioxide (CO_2) supply for the enrichment of the crop with carbon dioxide. According to the data provided by the company, a total of 216,000,000 m^3 CO_2 (= 395,712,000 kg CO_2) is produced annually from the cogeneration system, of which 170,000,000 m^3 CO_2 (= 311,440,000 kg CO_2 are released into the greenhouses, while the remaining 46,000 m^3 CO_2 (= 84,272 kg CO_2) are released into the air. The electricity produced by the cogeneration system is not used during tomato production but is sold. According to the company's data, the total operating hours of the 4 cogeneration machines are 5,000 per year, i.e., producing a total of 8MW*5,000 h= 40,000 MWh of electricity per year. Therefore, it is considered that the production (consumption) of an equal

Table 1 - Data used in the calculation of the energy required for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Electricity consumed	The amount of electricity consumed by the public electricity supply network	kWh	6,800,000
Electricity produced	The amount of electricity produced by the cogeneration system and is sold	MWh	40,000
Natural gas	The amount of natural gas that is consumed by the cogeneration system	MWh	150,000 *(= 540,000.000 MJ = 540 TJ)*
Lubricants	Lubricants of cogeneration system machines	kg	11,000
Carbon dioxide (CO_2)	Amount of CO_2 produced by the cogeneration system and released into the air	kg	84,272

Source: Authors' own work based on data provided.

amount of electricity from the public electricity supply network is avoided. Table 1 gives the data considered in the calculation of the energy required for the tomato production.

II. Water

The amount of water used during the tomato production process is recorded in Table 2.

III. Fertilizers

The quantity and the type of fertilizers used for the tomato production process are recorded in Table 3.

IV. Insecticides

The quantity and the type of Insecticides used for the tomato production process are recorded in Table 4.

V. Other materials

The quantity and type of other materials, such as tomato seeds, used in the production process and materials used as a substrate for planting are recorded. It is noted that the quantity and type of seeds used are not taken into account in the calculation due to a lack of suitable environmental data in the existing LCI libraries (Table 5).

VI. Final product packaging

The quantity of materials used to pack the tomatoes is recorded in Table 6.

VII. Maintenance of greenhouses

The greenhouses used by the company for tomato production are constructed of load-bearing frame and glass and are permanent structures with a useful life of more than 30 years. Therefore, in the context of the present study, the construction of greenhouses is not included for the evaluation of carbon footprint, but only their maintenance. Specifically, the quantity of mate-

Table 2 - Water used for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Water	Non potable water derived from drillings	m^3	120,000 *(= 120,000,000 kg)*

Source: Authors' own work based on data provided.

Table 3 - The quantity and the type of fertilizers used for the tomatoes production.

Record	*Measurement unit*	*Quantity*
Monopotassium hydrogen phosphate as a source of phosphorus (P)	kg	30,340.0
Calcium nitrate as a source of nitrogen (N)	kg	82,835.0
Potassium nitrate as a source of nitrogen (N) and potassium (K)	kg	78,507.0
Ammonia nitrate as a source of nitrogen (N)	kg	1,040.0
Urea for CHP (nitrogen compound)	kg	34,000.0

Source: Authors' own work based on data provided.

Table 4 - The quantity and the type of Insecticides used for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Insecticides	1. Insecticides with the active compound pyriproxyfen (pyridinyl derivatives). 2. Insecticides with the active compound spiromesifen (tetronic acid derivatives).	lt	250 (*262 kg)*

Source: Authors' own work based on data provided.

Table 5 - The quantity and the type of other materials used for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Seeds	Tomatoes seeds	Items	380,000 *(0.5 kg)*
Substrate for planting	Stone wool planting substrate	m^3	860 *(25 tons)*
Plastic parts	Planting supports made of plastic (polyethylene, PE)	kg	2,000
Metallic Parts	Small, iron parts for machinery, etc.	kg	1,000

Source: Authors' own work based on data provided.

Table 6 - Quantity of packaging materials of the products.

Record	*Description*	*Measurement unit*	*Quantity*
Packaging	Cardboard boxes	Item	1,100,000 *(481,800 kg)*

Source: Authors' own work based on data provided.

Table 7 - Quantity of packaging materials of the tomato products.

Record	*Description*	*Measurement unit*	*Quantity*
Maintenance of greenhouses per production period	Glass panes (glasses) without any special coating	m^2	150 *(1,500 kg)*

Source: Authors' own work based on data provided.

rials used for the maintenance of the greenhouses required during the annual tomato production period is recorded in Table 7.

VIII. Transportation of materials

The transports concern both the raw materials used for the production of the tomatoes that are transported by the various suppliers to the production facilities as well as the materials that arise after the completion of production and are transported to recycling units. According to the information provided by the company, these transportations are implemented with 20-ton payload trucks, according to Table 8. The last column of the table calculates the product of the quantity of materials (in tons) and the kilometer distance covered during transportation, a parameter required to calculate the environmental impact.

IX. Waste Management

Waste generated during the production process of tomato products, along with its management, is documented in Table 9. Regarding the recycling of oils used in the cogeneration system, relevant studies (Udonne, 2011; Pires & Martino, 2013) discuss the methods employed for recycling and analyze their environmental impacts. In the present study, it is assumed that the environmental benefits of recycling 1 kg of lubricant oil are equivalent to the benefits gained by avoiding the production of 0.4 kg of new lubricant oil.

X. Environmental Data

Considering the data regarding the quantities of materials consumed and the processes performed to produce tomatoes as they were

Table 8 - Data concerning the transport of materials to/from the facilities.

Materials	*Quantity (kg)*	*Transport distance to/ from the facilities (km)*	*Quantity * Distance (tn*km)*
Fertilizers	226,722	160	36,275.52
Insecticides	262	40	10.48
Packaging materials (Cardboard boxes)	481,800	160	77,088
Stone wool	25,000	3,000	75,000
Glasses	1,500	40	60
Plantation supports (plastic)	2,000	40	80
Oils of machines	11,000	160	1,760
TOTAL (Materials to the facilities)			190,274 tn*km
Waste for recycling	146,000	40	5,840
Waste to landfill	25,000	4	100
TOTAL (Materials from the facilities)			5,940 tn*km

Source: Authors' own work based on data provided.

Table 9 - Waste management.

Record	*Description*	*Measurement unit*	*Quantity*	*Management*
Natural tissues Leaves / stems	Leaves / stems	kg	120,000	Disposal as livestock products
Plastic components	Plantation supports	kg	2,000	Plantation supports
Lubricants	Machines oils	kg	11,000	Recycling by a specialized unit
Paper	Paper / cardboard packaging	kg	12,000	Recycling by a specialized unit
Metallic Components	Steel	kg	1,000	Recycling by a specialized unit
Stone wool	Planting substrate	kg	25,000	Disposal in a landfill

Source: Authors' own work based on data provided.

described previously, the appropriate environmental data are selected from existing environmental data libraries (LCI libraries, Life Cycle Inventory) (Table 10).

3.4. *Life Cycle Impact Assessment*

To assess the environmental impact of the tomato production process, the Global Warming Potential assessment method (IPCC, 2007, GWP 100a 1.01) is used with climate change coefficients for a 100-year time frame. This method was developed by the International Panel on Climate Change (IPCC, 2007; IPCC, 2021) and refers to the possible changes in the Earth's climate due to the concentration of chemical substances ("greenhouse gases") that trap heat from the reflection of sunlight, while under other conditions would pass outside the atmosphere. It focuses on quantifying the environmental impact on the equivalent amount of carbon dioxide produced. The results are calculated in kilograms of equivalent carbon dioxide (CO_2).

Table 10 - Environmental data libraries (Life Cycle Inventory).

Category	*Dataset*	*LCI Library*	*Geographical coverage*
Energy	Electricity, high voltage, production GR, at grid/GR U	Ecoinvent Unit Processes	Greece
Energy	Natural gas, burned in gas turbine/GLO U	Ecoinvent Unit Processes	International
Energy	Lubricating oil, at plant/RER U (kg)	Ecoinvent Unit Processes	Europe
Water	Water, completely softened, at plant/RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Fertilizer (P_2O_5)	LCA Food DK	Europe
Fertilizers	Fertilizer (K_2O)	LCA Food DK	Europe
Fertilizers	Calcium nitrate, as N, at regional storehouse/ RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Potassium nitrate, as K_2O, at regional storehouse/RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Ammonium nitrate, as N, at regional storehouse/RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Urea, as N, at regional storehouse/RER U	Ecoinvent Unit Processes	Europe
Insecticides	Pesticide unspecified, at regional storage/CH U	Ecoinvent Unit Processes	Europe
Packaging	Corrugated board boxes, technology mix, prod. mix, 16,6 % primary fibre, 83,4 % recycled fibre EU-25 S	European Life Cycle Database (ELCD)	Europe
Maintance	Float glass uncoated ETH U	ETH-ESU 96 Unit Processes	Europe
Other	Rock wool, at plant/CH U	Ecoinvent Unit Processes	Europe
Other	Polyethylene, HDPE, granulate, at plant/RER U	Ecoinvent Unit Processes	Europe
Other	Cast iron, at plant/RER U	Ecoinvent Unit Processes	Europe
Recycling	Livestock feed (soy)	LCA Food DK	Europe
Recycling	Recycling PE B250	BUWAL 250	Europe
Recycling	Recycling paper B250	BUWAL 250	Europe
Recycling	Recycling ECCS steel B250	BUWAL 250	Europe
Disposal	Disposal, mineral wool, 0% water, to inert material landfill/CH U	Ecoinvent Unit Processes	Europe
Transport	Transport, lorry, 20-28t, fleet average/CH U	Ecoinvent Unit Processes	Europe

Source: Authors' own work.

4. Results and discussion

4.1. *Results*

Table 11 presents the results of the calculations concerning the equivalent produced carbon dioxide that corresponds to the materials consumed and the processes required to produce tomatoes. The total CO_2 emissions resulting from these activities during a growing season (7,500 tons of tomatoes) amount to 3,779,618.59 kg CO_2 eq. or 0.50395 kg CO_2 eq. per kilogram of tomatoes.

Table 12 presents the results of the calculations concerning the equivalent produced carbon dioxide that corresponds to the management of the waste resulting from the production of tomatoes, both for recycling and disposing in landfills. The total carbon footprint from waste management is -34,783.01 kg CO_2 eq. (or -0.00464 kg CO_2 eq. per kg tomato), indicating that the waste management process actually contributes a net reduction in carbon emissions, mainly due to recycling efforts. This is a key aspect of sustainability in agricultural systems,

Table 11 - Quantity of the equivalent CO_2 to produce tomatoes.

Materials/ Processes	*Equivalent CO_2 produced per growing season (7,500 t) (kg CO_2 eq.)*	*Equivalent CO_2 produced per kg tomato (kg CO_2 eq.)*
Energy		
Electricity consumed	6,894,931.51	0.91932
Electricity produced and sold	-40,558,420.62	-5.40779
Natural gas consumed in the cogeneration system	36,154,335.75	4.82058
Lubricants	11,762.74	0.00157
Carbon dioxide released	84,272	0.01124
Water	3,189.73	0.00043
Fertilizers	551,600.67	0.07355
Insecticides	1,834.09	0.00024
Other materials	41,939.91	0.00559
Packaging	554,737.75	0.07397
Maintenance of greenhouses	1,541.97	0.00021
Transport of Materials to the facilities	36,745.95	0.00490
Transport of Materials from the facilities	1,147.14	0.00015
TOTAL	3,779,618.59	0.50395

Source: Authors' calculations.

Table 12 - Quantity of the equivalent CO_2 of waste management after the production of tomatoes.

Waste management	*Equivalent CO_2 produced per growing season (7,500 t) (kg CO_2 eq.)*	*Equivalent CO_2 produced per kg tomato (kg CO_2 eq.)*
Disposal of natural tissue waste as livestock products	-27,140.81	-0.00362
Recycling of plastic parts by a specialized unit	-664.10	-0.00009
Recycling of lubricants by a specialized unit	-4,705.10	-0.00063
Recycling of cardboard packages by a specialized unit	-761.66	-0.00010
Recycling of metallic parts by a specialized unit	-1,688.39	-0.00023
Disposal of stone wool in a landfill	177.04	0.00002
TOTAL	-34,783.01	-0.00464

Source: Authors' calculations.

as it demonstrates that proper waste management can mitigate the overall carbon footprint. Below is an analysis of key contributors:

- Significant reductions in CO_2 emissions come from the recycling of various materials. For instance, the recycling of plasticparts (-664.10 kg CO_2 eq.) and lubricants (-4,705.10 kg CO_2 eq.) offsets the overall carbon impact. This suggests that the adoption of recycling initiatives can play a crucial role in reducing the carbon footprint of tomato production.
- The disposal of natural tissue waste as livestock products results in a negative

Table 13 - Total quantity of the equivalent CO_2 to produce tomatoes.

Environmental Impacts	*Equivalent CO_2 produced per growing season (7,500 t) (kg CO_2 eq.)*	*Equivalent CO_2 produced per kg tomato (kg CO_2 eq.)*
Materials/Processes	3,779,618.59	0.50395
Waste Management	-34,783.01	-0.00464
TOTAL	3,744,835.57	0.49931

Source: Authors' calculations.

Table 14 - Comparison of the equivalent carbon dioxide.

Standard Cultivation	*Production of Equivalent CO_2 ha^{-1} in Florida, USA*	*Production of Equivalent CO_2 ha^{-1} in Greece (greenhouse)*	*Difference*
Fertilizers	1,656 kg CO_2 eq ha^{-1}	1,032 kg CO_2 eq ha^{-1}	-37.68 %
Insecticides	3,268 kg CO_2 eq ha^{-1}	1,834.09 Kg CO_2 eq ha^{-1}	-43.87 %
Water	5,976 kg CO_2 eq ha^{-1}	3,189.73 Kg CO_2 eq ha^{-1}	-46.62 %
TOTAL	52,813 kg CO_2 eq ha^{-1} (0.75 kg CO_2 per kg)	35,226 kg CO_2 eq ha^{-1} (0.49931 kg CO_2 per kg)	-33.3%

Source: Readily available data from Jones et al. (2012). - Authors' calculations.

carbon impact of -27,140.81 kg CO_2 eq., further enhancing the sustainability of the production process. Conversely, the disposal of stone wool in a landfill leads to a very small positive contribution of 177.04 kg CO_2 eq., which minimally impacts the overall carbon footprint.

The sum of the environmental impact caused, on the one hand, by the materials consumed and the processes followed to produce the tomato product and, on the other hand, by waste management, gives the total environmental impact of the final product (tomatoes). These results are presented in Table 13. The overall CO_2 footprint for producing 7,500 tons of tomatoes is 3,744,835.57 kg CO_2 eq. or 0.49931 kg CO_2 eq. per kg of tomatoes.

4.2. *Comparative analysis and discussion*

Although direct comparison of produces from different agricultural areas and different production methods (conventional and organic methods) is difficult, the following table presents a comparison between the LCA results of the current study and results presented in the study of Jones *et al*. (2012). Although the production methods and system boundaries could vary, the comparison enables us to have better understanding on impacts of tomato production under different conditions (greenhouse-based production and open-field based production). Table 14 gives a comparison of the equivalent carbon dioxide produced in a typical crop in Florida, USA, with the corresponding Greek one. The selection of the specific area was made because the climatic data are similar to the Mediterranean climate, which also exists in the area of the unit, but also because, unfortunately, both at the national and European level, there are very few studies related to the production of carbon dioxide during the production of tomatoes. It should be noted that this unit uses drip irrigation.

According to Jones *et al*. (2012), the production of equivalent carbon dioxide from the production of tomatoes in open-type crops can reach up to 0.75 kg CO_2 per kg of product produced. The production of tomatoes in the controlled environment of the greenhouse results in a reduction of the emitted carbon dioxide equivalent by 33.3%. A percentage that proves the impressive production possibilities as well as the energy savings realized during the production process. It is also evident that a substantial portion of the carbon dioxide emissions originates from the consumption of electricity and natural gas, while a smaller fraction is generated through the use of water, fertilizers and insecticides.

5. Concluding remarks

5.1. *Conclusions*

The objective of the present study is to calculate the environmental impacts caused by the different stages of the production of tomato products using the valuation method regarding the equivalent carbon dioxide (CO_2) that is produced. The Global Warming Potential valuation method was used to assess the environmental impacts with climate change coefficients over a 100-year time frame, while the results were calculated in kilograms of equivalent carbon dioxide (kg CO_2 eq.). The impacts of the materials consumed and the processes performed during the production process under consideration were calculated to be equal to 0.50395 kg CO_2 eq. per kilo of tomatoes. Accordingly, an environmental benefit resulting from waste management after the completion of the production process was calculated to be equal to 0.00464 kg CO_2 eq. per kilo of tomatoes. This benefit is subtracted from the effects of materials and processes and the total environmental impact caused is obtained equal to 0.49931 kg CO_2 eq. per kilo of tomatoes.

The calculations prove that the energy required to produce the tomato is the factor that has the greatest impact on the environmental impact. The overall effects of this energy depend directly on the amount of electricity produced by the high efficiency cogeneration (CHP) system with natural gas consumption, as well as the amount of electricity consumed for production from the public network. The fertilizers and the materials used to package the product also affect the overall environmental impact. As far as the management of the waste resulting from the production process is concerned, a significant environmental benefit arises from the disposal of natural tissues as livestock products, mainly due to their increased quantity, as well as from the recycling of the lubricating oils used in the machines of the cogeneration system.

5.2. *Policy implications*

On the outcome of policy, the findings of the present study could provide guidance to policymakers and practitioners in developing effective strategies that promote sustainability in tomato production and supply chain while reducing environmental impacts. The results provide important insights into the carbon footprint of tomato production and highlight areas where emissions can be reduced or offset. Particularly:

1. The use of cogeneration systems and the production of surplus electricity to be sold can significantly reduce the carbon footprint, showing a potential path toward more energy-efficient and sustainable tomato production. The positive offset from electricity production is a clear benefit that could be further optimized. Additionally, adopting renewable energy sources (solar, wind, or geothermal) for heating and cooling could significantly reduce the reliance on fossil fuels. Policymakers can incentivize the implementation of such systems and also the use of renewable energy sources through subsidies or tax breaks for energy-efficient technologies.
2. Recycling and the disposal of waste materials in environmentally responsible ways provide opportunities for reducing the overall carbon impact. The recycling of materials like plastic, lubricants, and cardboard can substantially lower emissions, making it a critical area for improving sustainability in tomato production systems. Policymakers can support the development of waste management infrastructure, providing incentives for promoting the adoption of closed-loop systems where waste is reused or repurposed.
3. The emissions from fertilizer use and packaging materials represent significant contributions to the overall carbon footprint. To mitigate this impact, policymakers can promote sustainable agricultural practices such as precision agriculture, which uses technology to apply fertilizers more efficiently, reducing excess and minimizing emissions. The promotion of organic or less energy-intensive alternatives to chemical fertilizers could also be considered. Additionally, encouraging the adoption of biodegradable or recyclable packaging

materials can help lower emissions associated with packaging waste.

By addressing issues such as energy consumption, waste management, and the use of fertilizers and packaging, policymakers can foster a more sustainable agricultural system for the tomato industry at a national or regional level, thereby contributing to the broader EU's agenda on climate change mitigation and sustainable production.

5.3. *Limitations*

A certain limitation of this study is tied to its exclusive focus on the environmental impact of tomato production, specifically the carbon footprint, without incorporating economic considerations. While the environmental aspect is critical for understanding sustainability, economic factors, such as the costs of production, market dynamics, and financial feasibility of emission reduction strategies, are equally important for a holistic assessment. Future research could integrate cost-benefit analyses and economic evaluations to complement the environmental findings and provide a more comprehensive framework for policy formulation.

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Water management for agriculture in a Mediterranean area: The case of processing tomatoes in Italy

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Abstract

Unpredictable climate variations, including severe droughts and heat waves, pose significant challenges to agricultural water management and threaten the economic sustainability of farmers. This study examines the effects of different irrigation methods and water supply services on the economic performance of farmers in the processing tomato sector, using micro-level data from the Italian Farm Accountancy Data Network (FADN) from 2008 to 2021. The analysis reveals economic benefits generated by adopting a self-supply water management strategy and more sustainable irrigation techniques (micro-irrigation), especially in regions experiencing acute droughts and higher temperatures. Findings emphasize the importance of considering the region-specific context when implementing policy interventions, technological innovations, and governance structures, particularly in Mediterranean countries where water scarcity increasingly restricts agricultural output.

Keywords: *Agricultural water management, Processing tomato industry, Adaptation measures, FADN, Italian agriculture.*

1. Introduction

Agriculture remains one of the main sectors in Mediterranean countries that face binding limits on water scarcity. Climate change and warm heat are exacerbating water stress, highlighting more and more that irrigated agriculture will be essential to guarantee food security and farmers' income sustainability in the future (World Bank, 2022a). Even if rainfed agriculture remains the predominant agricultural production system worldwide – 78% of world agricultural land (FAO, 2021) –, a permanent source of irrigation is becoming necessary to maintain productivity and sectorial competition also in temperate zones. According to the Food and Agriculture Organization (FAO, 2021), in the Mediterranean basin, 17% of agricultural land is irrigated in West and Central Europe, compared to 31% in North Africa. The challenges posed by climate change are, in fact, constantly increasing the demand for agricultural water, especially for water-intensity crops.

Water scarcity, affecting agricultural produc-

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tivity, is limiting the capacity of local systems to respond to consumers' demand while increasing the import dependence from other countries. As a result, sustainable irrigation strategies will be pivotal not only to climate change adaptation and mitigation but also to support the economic competitiveness of local agrifood systems and farmers' income. The economic resilience of local systems will depend on the adoption of water management models and irrigation systems capable of considering all the sustainability dimensions comprehensively and harmoniously. The relationship between economic activities and water consumption is, thereby, emerging as a central concern within the broader environmental issues, positioning it as a strategic objective in the green transition of Mediterranean agri-food systems. To improve the efficiency of water governance in the agriculture sector policies should consider both demand and supply side (Behera *et al.*, 2023; Shiferaw *et al.*, 2023; Tran & Cook, 2023), looking also at the non-conventional grey solutions (e.g., Tran & Cook, 2023).

Irrigation schemes and water governance strategies are the main channels along which policy interventions may build economic resilience to water shocks and stresses, indeed.

On the one hand, the adoption of different irrigation technologies (e.g., micro-irrigation *vs* sprinkler) will operate at the farm level and affect how water resources are managed by farmers. On the other hand, the establishment of efficient and harmonised regional/national water distribution services may guarantee the availability of water and its fair allocation by crops' irrigation water requirements and their economic returns. As recently described by Scatolini *et al.* (2024) irrigation water requirements affect crops' economic value and "*the estimation of the socio-economic effects of specific irrigation techniques should be addressed by agricultural economists*" Scatolini *et al.* (2024, p. 18). Evaluating the economic impacts of agricultural water management and irrigation strategies is, however, a complex task, and there is currently no consensus on the appropriate methods or criteria for such assessment.

In this context, this paper aims to investigate the relationships between different irrigation schemes, supply irrigation services and the economic sustainability of Italian farmers specialised in a water intensity specialisation: the processing tomato industry.

Italy is the ideal empirical setting for several reasons. First, Italy is the EU country with the highest number of irrigated plots which are watered at least once a year, with peaks in the spring and summer seasons (Wriedt *et al.*, 2009; CREA, 2023). Second, it is one of the Mediterranean countries most actively engaged in high-value-added production, due to its leadership in both the processing and processed agrifood sectors. Among them, the processing tomato industry (e.g. tomatoes used for pulp, peeled tomatoes, purees and ready-made sauces), is a strategic market for the Italian agrifood sector competitiveness, at both national and international levels. In 2023, Italy dedicated approximately 68,500 hectares to cultivating tomatoes for processing, with an increase of around 5% compared to 2022. However, in the same year, the production (5.4 million tonnes) registered a decrease of 1.3% mainly due to the extreme climatic events and an unfavourable climate that have led to a decline in the production yield per hectare (Cammarano *et al.*, 2022).

Over the years, the literature demonstrated that environmental production inputs, like water, represent a key factor for economic sustainability, given their higher volatility and dependence on climate change in comparison with other artificial inputs (e.g., fertilizers). In the case of water, it is a necessary input, very often characterised by low substitution rates, which might yearly determine the land productivity rate, the amount of production and its economic value and the productivity rate. In this sense, adopting different irrigation techniques and water management strategies may generate economic value and prosperity for farmers. The economic sustainability of agriculture holdings is nowadays constantly endangered by climatic conditions, which are exacerbating farmers' entrepreneurial risks. In Italy, over the last few years, agriculture has faced threats from unpredictable climate variations, especially in temperature and precipitation. Overall, all regions have witnessed a rise in severe drought profoundly affecting crop yields in some of the most agriculturally crucial areas of the country. These climatic conditions have affected irrigation strategies and local water availability, posing location-specific challenges for agricultural production, and affecting prices and economic outputs (ISTAT, 2021). Several are the economic variables that the literature has defined as good proxies of economically sustainable targets (Sardone *et al*., 2023), such as Gross Sealable Production (GSP) and Value Added (VA), and all of them might be, at least theoretically, affected by the availability of water.

From the EU policy perspective, keeping together economic and environmental objectives is becoming a target goal, with a growing integration of economic and environmental tools, as shown in the new Green Deal, the Farm to Fork strategy and the 2023-2027 Common Agricultural Policy (CAP) programming period (Henke *et al*. 2018; Henke *et al*., 2023). All these documents advocated for new adaptation and mitigation strategies, with the general aim of improving the resilience of agriculture, while fostering the economic competitiveness of the sector (Seneviratne *et al*., 2015).

The main contribution of the paper is providing evidence about the adoption of micro-irrigation, which seems to positively support the economic sustainability of farmers involved in the tomato industry. This evidence is in line with the goal of the new CAP of reducing the volumes of water while keeping in or even increasing, the economic performance of farmers thanks to more efficient use of water.

However, some regional heterogeneity emerges suggesting the need to reflect on the territorial dimension of water governance efficiency. The approach to tailor interventions to crop and territorial species, which is already implemented for other agricultural policy measures, may, in fact, lead to more sensitive strategies that contribute to implementing a more rational and sustainable use of water for irrigation.

Products, such as ready-made tomato sauces and pulp, represent a key driver of the Italian economic value and competitiveness for the agrifood sector, in both domestic and international markets. Given the water intensity requirement of this crop (i.e., tomato), addressing water scarcity and extreme precipitation events is becoming not only an agronomic challenge (Donati *et al*., 2023) but also an economic one (Mantino *et al*., 2018). In the long run, a production reduction may lead to an increase in terms of prices and, consequently, determine a change in the economic nature of this good, from a normal good to a luxury one. On the one hand, converting this farming activity into a niche market may help Italian producers differentiate and diversify their products based on their quality and geographical origin. On the other hand, however, the risk may be to be crushed by the cheaper international competitiveness. However, the positive relation between new irrigation techniques and the GSP, found in this study, leaves some optimism about the possibility of not excessively limiting production.

The paper is structured as follows. Section 2 introduces the literature and contextual framework, with a specific focus on the sector under analysis. Section 3 presents the empirical setting, data and methodology, while Section 4 describes the results. The conclusion provides some final remarks and policy advice.

2. Literature review and contextual framework

Agriculture is responsible for 24% of the current extraction of water in Europe, with Italy, Spain, Greece, France, and Portugal accounting for 96% of the total extraction (European Environmental Agency Water Resources Across Europe, 2021). Considering the projected increases in temperatures and droughts in the coming years (Mirra *et al*., 2023; Fallon *et al*., 2010), water stress has now become a more permanent condition rather than an occasional event, making irrigation a necessary condition for the sector. Contrasting water stresses through governance and management strategies and irrigation techniques are becoming, therefore, a crucial topic in the political and academic debate about the sustainability of agrifood systems (Martin-Ortega *et al*., 2011; European Environmental Agency Water Resources Across Europe, 2021)[1].

2.1. *Water management and irrigation techniques*

The economic sustainability of farmers could be affected by the implementation of different water management strategies and irrigation techniques. Water represents, in fact, not only a cost but also a necessary production factor without which tomato production cannot be guaranteed. The uneven distribution of water in different regions of the world, including Europe, and the growing competition for water use, call for sustainable management of available water resources, at different territorial levels considering specific strategic options: from "virtual water" to improved efficient use of irrigation water, to recycling and depollute water making it available again for irrigation and drinking uses (Qadir *et al*., 2003). Research on water management and efficiency has improved substantially in the last years and is more and more oriented to better understand how the complex interactions between different uses of water and agriculture productions may develop over the coming decades and the consequent social, political, and environmental implications (Cosgrove and Loucks, 2015).

Among others, Mendicino *et al*. (2008) underlined how a reactive approach to prolonged water shortage is not particularly appropriate in a context where water is scarce, such as the Southern regions. Conversely, adopting a proactive approach, based on mitigation measures with the direct and constant involvement of all the stakeholders, should reduce the levels of subjectivity, while increasing transparency and participation by leading to optimistic results in terms of water management. Vanino *et al*. (2015) studied the implementation of Earth Observations (EO) techniques which result to be highly responsive to irrigation issues and water management in water scarcity territories. These techniques combine technical information, such as weather parameters and crop characteristics, with management and environmental factors, helping to implement more efficient water use. Staccione *et al*. (2021) investigated water retention ponds in the North and demonstrated that investment costs and running costs are relatively modest, considering the benefits in terms of an increase in agricultural production and the provision of ecological services. Water retention ponds are, in fact, not only water stocks but also a potential ecological source of biodiversity and micro-habitats.

From the governance perspective, the strategies adopted are characterised by different strengths and weaknesses. Collective supply services are more suitable to manage water distribution and respond more efficiently to water scarcity crises. These services are assumed capable of achieving higher levels of distribution efficiency (Manganiello *et al*., 2022; Scardigno *et al*., 2011) and environmental sustainability (Dono *et al*., 2014), thanks to their centralised nature and top-down management. Economies of scale can, in addition, reduce extraction and distribution costs. Planned collective supply management allows farmers to use surface water, rather than deep water from the aquifer, which significantly reduces the risk of subsidence. However, the quantity of water provided by *Consortia* is often not sufficient, so farmers need to obtain water also from private wells, with significant effects on the impoverishment of the aquifers and the unsustainable use and distribution of water (Giannoccaro *et al*., 2019). The implementation of collective services, however, needs to be implemented with caution, given that, the increasing extreme climatic events that are affecting Mediterranean areas may require a

[1] Water scarcity implies a condition of seasonal, annual, or multiannual stress, caused by anthropic activities, due to a systematic excess of demand compared to the supply capacity of a natural system, which in turn depends on the relationship between renewable reserves and the extraction and use of water. Drought, instead, is a natural and temporary phenomenon occurring when the average water availability reduces due to a scarcity of rainfall (European Environmental Agency Water Resources Across Europe, 2021). Drought can be aggravated in a situation where water scarcity is frequent and the unbalance between water demand and the supplying capacity of the natural system.

just-in-time response, which a collective supply of services is always not capable of providing.

Conversely, farmer-led water provision, for which users are not subject to *Consortia* regulations and timelines, leads to lower costs, guarantees just-in-time provisions and offers high-quality water, especially in the short run (Sardaro *et al*., 2020; Tauro *et al*., 2024). This difference in water quality may be capitalised in land value, becoming an additional source of economic benefit for farmers (Tauro *et al*., 2024). In sum, the choice between collective and self-supply irrigation from private wells represents a key challenge for both farmers, who would like to reduce the time of provisions, and policymakers, who must design efficient and inclusive market regulations.

At the same time, the adoption of different irrigation techniques has also become crucially important. Producers of processed tomato production mainly adopted sprinkler irrigation and micro-irrigation (Manganiello *et al*., 2022)[2]. On the one hand, sprinkler irrigation is particularly useful in areas where water is scarce or where the terrain is not suitable for traditional surface irrigation methods. Sprinkler irrigation can be automated and adjusted to supply precise amounts of water, making it an efficient and effective irrigation technique. On the other hand, micro-irrigation is suitable to address water scarcity given that it minimises evaporation and runoff, making it more water-efficient than traditional surface irrigation methods. A relevant stream of studies focused on this issue, and in particular on the improvement in irrigation efficiency at the field level, analyzing the so-called "rebound effect", according to which an improvement in efficiency does not necessarily translate into a reduction of the consumption of water (Berbel *et al*., 2018). Following these authors, to properly study the relationship between efficient irrigation and water consumption a set of tools needs to be considered, such as the potential area irrigated, the crop changes and also market forces.

2.2. *The economic effects of water use*

With specific regard to the economic effects of water scarcity, some papers exist that looked at the relationship between water issues and economic performances in Mediterranean countries. Babovic *et al*. (2009) worked on the economic efficiency of irrigated and dry crops in a local area in Serbia (Vojvodina), comparing data and analysing the economic performance before and after the introduction of irrigation. Results show a positive effect of irrigation on production yield and farm profitability. Ruberto *et al*. (2022) looked at the use of water in agriculture in the Veneto region in Italy with microdata (source: FADN), showing that irrigation increased the value of agriculture turnover. Lopez-Serrano *et al*. (2021) assessed the use of reclaimed water in greenhouses used in agricultural production in a region of Southern Spain (Almeria), which has positive effects not only on the quantity of water saved but also on the quality of soils. Other studies have investigated the economic benefits of water requirements and irrigation strategies. Lopez-Mata *et al*. (2019) built an integrated framework to predict the direct economic impacts of drought on irrigated agriculture, concluding it is relevant in terms of production loss. Giannoccaro *et al*. (2019) empirically assessed the impact of the reduction of water availability on tomato production in the *Capitanata* area in the Italian Apulia region showing that drought has caused losses of 30% compared to years with regular water availability. Alobid *et al*. (2022) worked on the efficient allocation of water in Southern Italy, looking at farmers' productivity and comparing scenarios aimed to achieve the most suitable set of decisions that fulfil the best goal in terms of efficient use of water. More recently, Scatolini *et al*. (2024) estimated the impact of crops' irrigation water requirements on economic value (i.e. yields and gross saleable production) in the Emilia-Romagna region sug-

[2] Sprinkler irrigation is a method of distributing water to crops like natural rainfall through a system of pipes, usually by pumping, and then sprayed into the air through sprinklers so that it breaks up into small water droplets that fall to the ground. Conversely, micro-irrigation is a method of distributing water directly to the root zone of plants.

gesting that, in water scarcity conditions, the allocation of water to permanent crops generates economic benefits also for small quantities of water.

Looking at the tomato sector, existing papers about the evaluation of the effects of different irrigation systems are even more scant and rarely focus on economic outcomes.

While Giannoccaro *et al*. (2019) investigated the impact of the reduction of water availability on the quantity of production, Rinaldi *et al*. (2009) estimated the effect on biomass, berry production and water use efficiency. They also included an analysis of the consequences on net agricultural income. Cammarano *et al*. (2022) studied the effect of climate change on the quantity of water used in processing tomatoes in South Italy (Campania region), showing that an increase in irrigation water does not translate into a growth of production and yields. In a different context, Rogers *et al*. (2014) worked on the choices of irrigation systems in the production of processing tomatoes in Florida, US. They showed how the switch to more efficient irrigation systems led to increases in production and quality, at the same time reducing energy costs and the quantity of water.

Other studies combine the sectoral analysis of the processing of tomatoes with the application of specific methods of irrigation and techniques. This is the case for Pandey *et al*. (2018), who investigated the economic effect of wire and wire drip irrigation on tomato crops in India, showing the economic advantages of the former compared to the latter, all other terms being equal. El Chani *et al*. (2023) focused on a water management issue, focusing on the optimization of applied irrigation water for different high-quality products, including processing tomatoes, concluding that low-cost wireless soil moisture sensors are effective in managing the level of irrigation by optimising the processing tomato yield and the economic benefits for farmers.

Despite the growing literature, a detailed empirical analysis of the relationship between the localisation of crops, sources of water, on-field irrigation systems and economic performance of farms does not exist so far. In this paper, we try to disentangle these complex relations, which are particularly relevant for a crop that is one of the most important Italian value chains.

3. Processing tomato growing, and water needs in Italy

Italy is firmly confirmed to be the third-world producer and processor of tomatoes, after the USA and China, with 6.6 million tons and a total value of 1.3 billion euros in 2021-2022 (Cammarano *et al*., 2022). The Italian sector maintains the leadership also in terms of international competition, with 2.8 million euros of exports in 2023 (ISMEA, 2024). Over the years, there has been, however, a decline in production, influenced by various factors. First, there was a progressive replacement of lower service-content products (pulp and peeled tomatoes) with higher service-content products (purees and ready-made sauces), which include a lower percentage of tomatoes. Second, changes in consumer behaviours have led to a gradual reduction in the number of meals consumed at home, in the time dedicated to preparing meals and in the use of tomato sauces, replacing them with other types of condiments. Third, even if the level of CAP funds destined for this sector in Italy remains the highest among EU countries, there was a decrease in absolute terms of the amount of public support (Arfini *et al*., 2011; Kierczynska, 2015)[3]. Lastly, the recent increasing temperatures and water stress conditions have even more affected the production capacity. Tomato is, in fact, a

[3] At the EU level, Italy remains the main beneficiary of the CAP support for the sector, through two main channels: the common market organisation (CMO) measures and the rural development programmes [28]. Funds from the CMO are mainly oriented to producer support and consumer behaviour (e.g. *Fruits in the school* EU programme (*Commission Implementing Regulation (EU) 2017/39 of 3 November 2016 on rules for the application of Regulation (EU) No 1308/2013 of the European Parliament and of the Council about Union aid for the supply of fruit and vegetables, bananas and milk in educational establishments (OJ L 5, 10.1.2017, p. 1)*). Conversely, resources coming from the rural development programmes mainly address support quality productions (e.g. quality schemes) and innovation diffusion.

water-intensive crop that requires to be irrigated and that is negatively reacting to climate changes and extreme events (e.g., precipitations) (ISTAT, 2023). Unconventional water use is not allowed (e.g., wastewater), leaving water allocation and management decisions strategic for this sector.

In Italy, Piacenza is the area where at the turn of the twentieth century the industry of processing was born, becoming a virtuous example of a localised agri-food system characterised by the interaction between private and public actors. Nowadays, the production is mainly concentrated in two regions: Emilia-Romagna in the North (provinces of Piacenza, Parma and Ferrara) and Apulia in the South (province of Foggia) (Table 1)[4].

These two regional systems differ quite substantially in terms of agricultural water needs, consumption, and distribution (Zucaro, 2011). For example, Apulia requires large amounts of irrigation due to the scarcity of water and the higher temperatures. From the irrigation governance perspective, the main difference regards the distribution services adopted. While in Emilia-Romagna the distribution of agricultural water is mainly managed collectively, in Apulia it relies on self-supply services, despite an increase in the water provided by *Consortia.* In Italy, the institutional bodies responsible are the so-called *Consorzi di Bonifica e Irrigazione* (Land Reclamation and Irrigation Consortia), which manage the distribution and allocation of water, whereas in the case of farmer-led irrigation farmers who have obtained the concession to pump water are responsible for all the process and all the costs for the sourcing, catchment and distribution of the resource. The diffusion of *Consortia* in Italy can be assumed as a good practice of institutional references for water management that could create the conditions in which farmers can adopt more sustainable practices on a large scale, obtain training and technical assistance, establish incentives for rational irrigation, and promote water-efficient practices through shared regulations and standards.

Table 1 - Processing tomatoes in Italy (2021).

	Area (thousand ha)	*Production (tons)*	*Yield (kg/ha)*
North	38,621	3094	80.1
South	32,569	2484	91.2
Italy	71,19	5578	85.2

Source: Authors' elaboration from Eurostat and OI Processing Tomato data.

Regarding irrigation technologies, while in Emilia-Romagna sprinkler irrigation is the most common irrigation system, in Apulia micro-irrigation prevails, confirming the preference for micro-irrigation as a suitable approach to contrast higher temperatures. At the same time, the water scarcity affecting the Southern part of the country is reflected by the fact that the average number of irrigation days in Apulia is lower than in Emilia-Romagna, 5 days and 20 days respectively[5].

Due to the economic value of tomato processing production for Italy, its high-intensity water requirements and the actual water scarcity challenge, understanding the potential consequences of different water management strategies with a broader spectrum of analysis, is crucial as never before. The new Italian strategic plan of the CAP 2023-2027 is the first attempt in this direction. It explicitly underlines how in the case of: "*the standard cultivation technique* [for processing tomato production] *involves the use of irrigation methods aimed at conserving water resources (micro-irrigation)*"[6]. However, how supporting farmers to achieve this objective is not mentioned, and there are no funds specifically targeting this issue to compensate for the economic discrepancy (i.e., fixed costs and initial investments).

4. Research design

To conduct the study, this paper uses a micro-level dataset at the farm level and exploits panel-fixed effects models to isolate the effect of irrigation schemes and water services on

[4] Province corresponds to the NUTS3 level according to the EU territorial nomenclature.
[5] Data on irrigation water days is available only from 2019 to 2021.
[6] IT 628 IT PD 06 - CIS(04) - *Sostegno accoppiato al reddito per superficie - Pomodoro da trasformazione*.

the economic performance of farms, measured through three key indicators: (i) Gross Sale Production (GSP), (ii) Value Added (VA), and (iii) net income (NI). Unlike previous research, which has primarily concentrated only on a single specific case (e.g., Giannoccaro *et al*., 2019) or not EU countries (Benmehaia and Brabez, 2018), this analysis encompasses all major production regions in Italy, thereby utilizing a substantially larger sample and providing more comprehensive insights into the sector's economic dynamics.

4.1. *Data and sample*

Data have been collected from the Italian Farm Accountancy Data Network (FADN), which is the primary source of annual micro-economic data for agricultural holdings within the EU[7]. This dataset allows us to account for the socio-economic dimension of farming and to obtain the needed information to account for the economic performances of farmers[8]. Data on climatic conditions have been collected from the ISTAT database, which provides information for temperature and precipitations at the NUTS3 level[9]. The climate context by which a farmer is affected has been determined by the *Provincia* (NUTS3) where the farmer is located.

Starting from the entire Italian FADN sample, we intentionally constructed our sample by selecting for each year all the farms involved in the tomato for industry production (>=1 ha) and located in Emilia-Romagna (North) and Apulia (South). The final sample is an unbalanced panel from 2008 to 2021 that includes for each year around 50 farms (734 observations in total)[10]. The regional distribution accounts for 68 per cent of farms in Emilia-Romagna, while 32 per cent in Apulia, with Foggia (Apulia) and Piacenza (Emilia-Romagna) as the NUTS3 with the highest concentration of farms[11].

Overall, over the years under analysis, there was an overall increase in the absolute value of UAA-dedicated tomatoes for procession in the sample, with, however, a constant average value by farms. If we look at regional statistics, both the absolute and the mean values had been higher in Emilia-Romagna than in Apulia. The absolute value of irrigated UAA for processed tomatoes increased, as well as the share of irrigated UAA (i.e., the share of the irrigated UAA dedicated to tomato for the procession on the UAA dedicated to this production). While Emilia-Romagna accounted for the highest average absolute value of irrigated land, the share of irrigated land for processed tomatoes is higher in Apulia.

The farmers' specialisation (i.e., the share of UAA dedicated to tomato for procession) remained quite constant over time, with an average value of 30 per cent. Regarding water, the total amount of water used for this crop increased by 32 per cent[12]. The average amount of water used in the regions under analysis is

[7] The Italian name is *Rete di Informazione Contabile Agricola (RICA)*.

[8] The Italian FADN includes all farms that achieve a threshold of standard output of a minimum of 8,000 EUR. Consequently, smaller farms are excluded from the sample. The economic dimension is defined as the sum of the standard output values of all agricultural activities carried out on the farm, and its value is expressed in euros. More information is available at: https://agridata.ec.europa.eu/extensions/FarmEconomyFocus/FADNDatabase.html.

[9] More details: https://www.istat.it/tavole-di-dati/temperatura-e-precipitazione-nei-comuni-capoluogo-di-provincia-anno-2022-serie-storica-2006-2022/.

[10] Unfortunately, the structure of the FADN dataset is not suitable for balanced panel data analysis, as the farmers surveyed change from year to year. Regarding the production specialisation, limiting the sample only to those farms specialised in tomato for processing (a threshold of 75 per cent of the share of UAA dedicated as defined by the EU) would result in a significant loss of observations: from 734 to 12.

[11] This regional difference in sample size is due to the FADN database construction. It relies, in fact, on a stratification based on three dimensions: Region, year and OTE (i.e., *Orientamento Tecnico Produttivo*). In this sense, the specific crop production is not considered in the EU sample stratification procedure. As a result, it could happen that there is heterogeneity in the regional location of farms if we focus on specific production.

[12] For FADN construction, this information is available only from 2011.

quite similar, with Apulia accounting for the highest values for all the years under analysis[13].

Regarding water management strategy, in our sample, collective management is more used in Emilia-Romagna, together with sparkling irrigation. Conversely, in Apulia private management and micro-irrigation are predominant. This evidence confirms sample validity.

The descriptive evidence can be attributed to several factors and anticipates some reflections. First, a potential increasing need to irrigate in a region characterized by severe drought, such as Apulia. Apulia accounts, in fact, not only for the highest number of hectares irrigated but also for the highest share of irrigated land. However, while the drought conditions in the Southern region are more severe, irrigation in Apulia is predominantly managed on an individual basis. Authorized farmers can withdraw groundwater and surface water as needed, without adhering to a collective plan like the one in place in Emilia-Romagna. Given that water is not entirely unavailable, farmers in Apulia likely responded to increasing droughts by extracting and using more water. In contrast, the less severe drought conditions in Emilia-Romagna may not have created such an urgent need for irrigation. The highest water need of Apulia is also confirmed by the increasing adoption of micro-irrigation techniques, which help face overall water scarcity.

Apart from the differences mentioned above, in these regions, there are some common trends related to farmers' characteristics that might affect the adoption of irrigation approaches that roll out possible sources of endogeneity making the results comparable. In both regions, family-owned is the most common ownership type of farmers, large farmers are the highest number, as well as farms with strong specialisation in comparison with diversified farms. The number of farms involved in organic production increases in both the regions under analysis. In addition, the average VA per hectare is quite similar (2.6 EUR/ha in Emilia-Romagna vs 3.3 EUR/ha in Apulia).

4.2. *Methodology*

To evaluate the economic effects of water supply methods and irrigation systems, this study adopts a panel-data approach with fixed effects[14]. The following model has been estimated with the constant:

$$\begin{gathered} \textit{Economic Performance}_{it} = \\ \alpha + \beta_1 \text{Collective-supply}_{it-1} + \beta_2 \text{Self-supply}_{it-1} + \\ \beta_3 \text{Sparkling}_{it-1} + \beta_4 \text{Micro-irrigation}_{it-1} + \\ \text{Controls}_{it-1} + \mu_t + \delta_{jt} + \varepsilon_{it} \end{gathered} \tag{1}$$

where *i* is the single farm and *t* is the year of the reference.

Economic Performance is declined through three variables, which literature has defined as good variables to register the economic dynamics at the farm level (Sardone *et al.*, 2023)[15]: (i) the farm's Gross Sale Production (GSP) of tomatoes for the processing industry, (ii) the overall farm's Value Added and (iii) the overall farm's Net Income (NI). While the GSP refers solely to tomato production, VA and NI refer to overall farm, indeed[16].

Collective supply and *Self-supply* are calculated by weighting the number of Utilised Agricultural Area (UAA) hectares managed by different agricultural water supply methods (self- *vs* collective supply) on the UAA dedicated to processing tomatoes. *Sparkling* and *Micro-irrigation* are also calculated by weighting the number of UAA hectares irrigated with different irrigation systems (micro- *vs*

[13] In 2021, the difference is only 1 thousand cubic meters.

[14] Based on the Hausman specification test.

[15] For an analysis of the microeconomic variables in agriculture see the FADN website on the EU Commission portal: https://agriculture.ec.europa.eu/data-and-analysis/farm-structures-and-economics/fadn_en.

[16] Unfortunately, the FADN database does not collect VA and NI separately for different crops. Conversely, the GSP is available for each specific crop produced by farms.

sparkling irrigation) on the UAA dedicated to processing tomatoes[17].

The model is augmented by a matrix of control variables with a one-year time lag (*Controls*) that includes: the farm's physical dimension (UAA - ha), the number of workers employed, the total amount of CAP funds received (EUR), the total costs specific for water consumption in proceed tomato farming (EUR), the percentage of UAA dedicated to tomato for industry, a dummy taking value 1 for organic farms (0 otherwise) and a dummy with value 1 for diversified farms (0 otherwise). In addition, we consider the annual average (°C) of temperature and precipitation (mm) of the NUTS3 where the farm is located to account for climatic conditions that vary at the provincial level. See Tables A1 and A2 in the Appendix for definition, source and descriptive statistics. In the model, we also include year-regional fixed effects (δ_{jt}) accounting for yearly cross-sectional changes varying at the regional level and year-fixed effects (μ_t) for yearly cross-sectional changes such as general shocks affecting agriculture production in a specific year (e.g., economic crisis, wars)[18].

Standard errors are clustered at the NUTS3 level (Abadie *et al*., 2017).

5. Results and discussion

Results of the model (1) are reported in Table 2.

Starting from the governance of irrigation services, findings reveal a statistically significant effect only for self-supply irrigation services, which are positively correlated with the Net Income (*Column 3*). According to the estimations, an additional point of the share of UAA supplied through a farmer-led source, and dedicated to processing tomato, is associated with an average increase in NI value of 13.940 euros, *ceteris paribus*. There seems to be, therefore, an economic advantage in using this type of irrigation supply, rather than managing water allocation and distribution through a collective approach, confirming what literature finds for arboreal crops (olive trees) (Tauro *et al*., 2024).

The significance of the NI is particularly relevant as it reveals a channel trough which seems to be possible to positively affect the structurally weaker economic position of farmers along the supply chain. The upstream position of farmers in the supply chain based on transformation and logistic activities, such as the processing of tomatoes, tends, to reduce their market power and negatively affect their economic performances. The increasing effect of self-supply irrigation services leaves, in addition, an open door to some reflections on the efficiency of the collective management strategy implemented so far, and on the opportunities of reforming them toward a more profitable solution.

Moving to irrigation methods (sprinkler irrigation *vs* micro-irrigation), findings reveal that micro-irrigation increases the GSP of proceed tomatoes (*Column 1*). The estimate indicates that, all else being equal, an additional point of hectare irrigated with a sprinkler system, and dedicated to farming tomatoes for the processing industry, is expected to generate an average increase of around 17,110 EUR in GSP. Conversely, there are no significant effects on VA and NI.

The results presented so far seem to be promising for the transition towards more sustainable agricultural systems of proceed tomato, even if, limited at the GSP. A decreasing trend in production is, in fact, one of the criticalities that Italian

[17] Regarding the empirical strategy adopted, we would like to clarify the following. First, unfortunately, FADN does not provide hectares irrigated by crops and the related specific water sources and irrigation systems. For this reason, we decided to weigh the related variables. Second, we decide to exclude the option of accounting for different water management strategies and irrigation techniques by a dummy. Even if this choice excludes the possibility of conducting interaction analysis, from the database, we cannot isolate, the number of hectares irrigated by micro /sparkling irrigation using water coming from collective/private supply. In this way, therefore, we would have lost the detail about the magnitude of the phenomenon, reducing the analysis only in the presence of it (i.e., yes/no) and capturing the effect at an aggregate level difficult to unpack. An additional analysis has been conducted to test our hypothesis and the results confirm the relevance of using more detailed variables. However, results are available upon request.

[18] The inclusion of these variables, at least partially, reduces the omitted variables bias that can be associated with the presence of inflation and responsible for changes in production and productivity.

Table 2 - Estimation results – entire sample.

	Gross Sale Production (1)	*Value Added (2)*	*Net Income (3)*
Collective supply	-1.790	7.770	3.356
	(4.016)	(4.573)	(4.216)
Self-supply	-1.783	16.16	13.94*
	(4.157)	(9.533)	(7.433)
Sprinkler irrigation	5.250	-0.996	3.038
	(4.289)	(3.575)	(6.322)
Micro-irrigation	17.11***	1.679	4.473
	(5.122)	(7.981)	(9.296)
Controls	Yes	Yes	Yes
Year-NUTS2 fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	377	377	377
R2	0.35	0.38	0.35

*Note: *** p<0.01, ** p<0.05, * p<0.1. The outcome variables are: (i) Gross Sale Production of tomatoes for processing (GSP), (ii) Value Added of farming activities (VA), and (iii) Net Income from farming activities (NI). They are expressed in thousands of euros. Controls include one-year time lag of the following variables: Utilised Agricultural Area, the number of workers employed, the amount of CAP funds received, the total costs specific for water consumption in proceed tomato, the percentage of UAA dedicated to tomato for industry, the percentage of UAA dedicated to tomato for industry, a dummy taking value 1 for organic farms (0 otherwise) and a dummy with value 1 for diversified farms (0 otherwise), the annual average of temperature of the NUTS3, the annual average of precipitation of the NUTS3, year-NUTS2 fixed effects and year fixed-effects. Robust standard errors in parentheses (NUTS3). The model has been estimated with constant and fixed effects.*

agriculture is facing (CREA, 2024) and, it seems that could be mitigated by new irrigation techniques. Conversely, when we extend the focus to the overall economic performance of farming, the effect is no longer significant. This evidence highlights the difficulties of achieving general spill-over economic benefits at the farm level by the adoption of more sustainable practices, suggesting a reflection on how to convince farmers to adopt innovations, given the potential limited economic benefits, at least in the short run. In the long run, a constant upward trend of GSP could compensate the highest cost of innovation and induce an increase also in farmers' remuneration and incomes.

However, the efficiency of specific policy interventions, or innovation strategies, may be affected by the institutional characteristics of the territory where it is implemented. In Italy, in fact, administrative regions maintain a certain level of legislative autonomy in water management. For this reason, we decided to investigate the regional heterogeneity by re-estimating the model separately for each region. Findings are reported in Table 3.

Looking at the agricultural water supply services, results show that in Apulia the collective supply services generate an overall higher negative effect on both VA (*Column 2*) and NI (*Column 3*) than self-supply. The effect is conversely not significant in the case of GSP (*Column 1*). In Emilia-Romagna, the only significant, and positive, effect is related to the self-supply services on NI (*Column 6*). The economic advantage of such an approach in a region mainly characterised by collective water governance can be ascribed to the just-in-time nature of farmer-led services. Starting from a baseline condition with water allocated in advance and by *Consortia* criteria, an additional positive effect can be driven

Table 3 - Estimation results – regional samples.

	Apulia			*Emilia-Romagna*		
	Gross Sale Production (1)	*Value Added (2)*	*Net Income (3)*	*Gross Sale Production (4)*	*Value Added (5)*	*Net Income (6)*
Collective supply	17.06	-20.84*	-27.71**	-1.879	5.430	2.160
	(9.210)	(8.086)	(6.703)	(4.723)	(4.757)	(3.554)
Self-supply	13.75	-17.83*	-20.96**	-1.509	16.50	14.40*
	(7.280)	(7.550)	(7.361)	(5.185)	(10.03)	(7.541)
Sprinkler irrigation	-6.369	35.04***	37.09***	4.460	-0.843	2.759
	(4.512)	(4.835)	(6.609)	(4.877)	(4.078)	(5.840)
Micro- irrigation	0.344	41.39***	47.35***	15.55	-2.729	-0.590
	(4.229)	(5.697)	(7.401)	(8.413)	(7.017)	(8.924)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	147	147	147	230	230	230
R2	0.46	0.42	0.37	0.34	0.41	0.37

*Note: *** p<0.01, ** p<0.05, * p<0.1. The outcome variables are: (i) Gross Sale Production of tomatoes for processing (GSP), (ii) Value Added of farming activities (VA), and (iii) Net Income from farming activities (NI). They are expressed in thousands of euros. Controls include one-year time lag of the following variables: Utilised Agricultural Area, the number of workers employed, the amount of CAP funds received, the total costs specific for water consumption in proceed tomato, the percentage of UAA dedicated to tomato for industry, the percentage of UAA dedicated to tomato for industry, a dummy taking value 1 for organic farms (0 otherwise) and a dummy with value 1 for diversified farms (0 otherwise), the annual average of temperature of the NUTS3, the annual average of precipitation of the NUTS3 and year fixed-effects. Robust standard errors in parentheses (NUTS3). The model has been estimated with constant and fixed effects.*

by the opportunity to extract water when it is needed and obtain it in a short time.

From a policy perspective, overall, looking at the potential social and environmental advantages of using collective services, this evidence suggests that, when well-managed, collective supply systems may function as an effective alternative without, however, generating substantial economic benefits. In a region such as Emilia-Romagna, historically managed through a collective approach, this governance model may become a standard governance framework that, even if without a positive impact, does not negatively affect the farmers' economic sustainability (as in Apulia).

Moving to the type of irrigation systems, findings reveal a positive and significant effect of micro-irrigation on farms' economic performances in Apulia: each additional point of the share of tomato for processing irrigated through a micro-irrigation result in an increase of 41,390 euro in VA, while of 47,350 euro in NI. Due to the highest level of drought that characterises this region, this evidence can be considered as an encouraging result for claiming in support of the positive economic consequences of the adoption of more sustainable irrigation technologies for the entire farm. The observed impact justifies and supports, the effort made by EU and international organizations towards the adoption of more sustainable irrigation services, recognised as essential to climate change mitigation (World Bank, 2022b).

The no significant impacts found in the case of Emilia-Romagna may be, at least partially, explained by the fact that large-medium farms, such as those that characterised this region, tend to be economically more robust and, therefore, potentially less financially dependent on water scarcity through new irrigation techniques. In this case, even though the adoption of more sustainable technologies does not contribute to economic value, it forever helps reduce environmental impact. The shift from more conventional irrigation techniques to micro-irrigation ones will lead to more environmentally sustainable agricultural systems, at both local and national levels (Mirra *et al.*, 2021; Tauro *et al.*, 2024).

6. Conclusions

Under the conditions of climate change, water management and irrigation practices have emerged as central issues in political and academic discussions regarding the sustainability of food production and agricultural systems (Scatolini *et al.*, 2024; Donati *et al.*, 2023; Martin-Ortega *et al.*, 2011). This study contributed to this debate by looking at the economic dimension of sustainability and highlighting how water issues (i.e., management and irrigation strategies) impact the economic performances of Italian farmers involved in processed tomato production.

In sum, our analysis highlighted the economic effects for farmers consequence of different agricultural water management and technologies adopted leaving two main general takeaways, which might be extended also to other crops.

First, it highlights that the adoption of different irrigation techniques became relevant for the economic consequences in territories characterised by higher temperatures, more severe water scarcity and lower levels of local added value systems (agriculture *vs* agrifood) and socio-economic development, as in the case of Apulia.

Second, the significance of self-supply services leads us to reflect on the potential diffusion of this approach in future, given the natural resources' vulnerability driven by the absence of top-down coordination. Although the study revealed that farm-led water supply is more economically advantageous for farmers, it could have negative environmental and social implications. Self-supplied irrigation is, in fact, not regulated by institutional plans and may generate quantitative and qualitative depletion of water as well as not fair management of water crisis (i.e., first comers). To avoid inefficient overexploitation of water, national and international policies might, therefore, promote the efficiency of collective services in tandem with the adoption of more innovative and efficient irrigation technologies.

This paper is fully supported by the EU and international policy debate[19]. First, agricultural water management may be ascribed as one of the policy channels through which local and national institutions may effectively shape the transition of local agrifood systems toward a more sustainable, resilient and economically fair approach. In doing this, the promotion of more innovative irrigation techniques should support practitioners and farmers in making evidence-based irrigation decisions (World Bank, 2022b). Second, both messages recall the relevance of considering where policy interventions, innovation technologies and governance structures are implemented. Our study underscores, in fact, the need for designing "water strategies" with a place-sensitive and crop-led approach. As for other objectives of political economy (Henke and Vaquero-Piñeiro, 2023; Crescenzi *et al.*, 2022), the logic of simple compliance and one-sized policies, summarised as the so-called "*one-size-fits-all*", does not work (Morisson and Doussineau, 2019). This aspect is particularly relevant within the international water law and regulation framework. At the EU level, the 2024-2027 CAP programming period is going towards this new direction, developing a policy closer to territories, societal needs and social equity and inclusion, enhancing the multifunctional role of agriculture and rural areas (Wilson, 2008; Tohidyan and Rezaei-Moghaddam, 2019). A sustainable use of water not only implies a more efficient use of on-farm resources but encourages also the provisions of eco-systemic services linked to the efficient and ration-

[19] The Agenda 2030 framework fixes the sustainable management and provision of clean water (SDG 6) as one of the goals, together with the promotion of sustainable agriculture (SDG 2) and terrestrial ecosystems (SDG 15). To achieve these goals, it is needed to address water scarcity issues, while guaranteeing agricultural production and food access.

al use of water as well as agro-biodiversity for more sustainable agricultural activities.

This paper is a starting point for future research on the economic sustainability consequences of water challenges under climate change. The extension of the analysis to other crops and EU countries, also in a comparative mode, is on our future research agenda.

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Appendix

Table A1 - Variables: definition, sources and units of measurement.

	Definition	*Source*	*Units of measurement*
Outcome variable			
Gross Sale Production	Revenues strictly connected with processing tomato farming activity	Italian FADN database	EUR - thousand
Added Value	Added value of total farming activities	Italian FADN database	EUR - thousand
Net income	Net income for total farming activities		EUR - thousand
Control variables			
Collective supply	Share of hectares managed by collective supply dedicated to processing tomatoes	Italian FADN database	Ha
Self-supply	Share of hectares managed by farm-led self-supply dedicated to processing tomatoes	Italian FADN database	Ha
Sprinkler irrigation	Share of hectares irrigated by sprinkler irrigation dedicated to processing tomatoes	Italian FADN database	Ha
Micro-irrigation	Share of hectares irrigated by micro-irrigation dedicated to processing tomatoes	Italian FADN database	Ha
Utilised Agricultural Area	Hectares of Utilised Agricultural Area	Italian FADN database	Ha
Number of workers	Number of people employed on the farm	Italian FADN database	Number
CAP funds	Amount of Common Agricultural Policy funds received by the farm	Italian FADN database	EUR
Water costs	Amount of cost for agricultural water dedicated to processing tomatoes	Italian FADN database	EUR
Specialisation	Percentage of UAA dedicated to processing tomatoes	Italian FADN database	
Organic farms	Dummy =1 for organic farms (0 otherwise)	Italian FADN database	
Diversification	Dummy =1 for the presence of diversification practices	Italian FADN database	
Annual average temperature	Annual average temperature for the NUTS3 where the farm is located	Authors' elaboration on ISTAT dataset	°C
Annual average precipitation	Annual average precipitation for the NUTS3 where the farm is located	Authors' elaboration on ISTAT dataset	mm

Table A2 - Descriptive statistics.

	Mean	*Std. dev.*	*Min.*	*Max.*
Outcome variables				
Gross Sale Production	136.83	147.90	0	1138.32
Added Value	238.16	509.87	4.36	10928.71
Net income	134.25	281.32	-319.16	6358.39
Control variables				
Collective supply	1.21	3.24	0	42.71
Self-supply	1.02	1.95	0	20.39
Sprinkler irrigation	1.20	2.88	0	42.71
Micro-irrigation	1.01	2.15	0	32
Utilised Agricultural Area	90.08	132.32	1.83	1659.24
Number of workers	4.14	8.09	0.50.50	131.61
CAP funds	57492.34	81428.2	0	787030
Water costs	1540.95	4369.75	0	43631
Specialisation	27.56	17.63	0.16	100
Organic farms	0.094	0.29	0	1
Diversification	0.08	0.27	0	1
Annual average temperature	430.83	700.09	13.78	1797
Annual average precipitation	2575.76	7418.573	271.7	78625

Table A3 - Estimation results with coefficients – the entire sample.

	Gross Sale Production (1)	*Value Added (2)*	*Net Income (3)*
Collective supply	-1.790	7.770	3.356
	(4.016)	(4.573)	(4.216)
Self-supply	-1.783	16.16	13.94*
	(4.157)	(9.533)	(7.433)
Sprinkler irrigation	5.250	-0.996	3.038
	(4.289)	(3.575)	(6.322)
Micro-irrigation	17.111***	1.679	4.473
	(5.122)	(7.981)	(9.296)
Annual average temperature	-0.009	0.003	0.015
	(0.010)	(0.038)	(0.039)
Annual average precipitation	0.0001	0.001**	0.0004**
	(0.0001)	(0.0002)	(0.0002)
Utilised Agricultural Area	1.471***	1.712**	1.485**
	(0.361)	(0.708)	(0.682)
Number of workers	1.367	-4.662	-8.795**
	(3.001)	(3.841)	(3.653)
CAP funds	-0.0005	-0.001*	-0.0009**
	(0.0004)	(0.001)	(0.0004)
Water costs	-0.002***	-0.001	-0.0005
	(0.0004)	(0.001)	(0.001)
Specialisation	1.592*	2.007***	1.725***
	(0.844)	(0.447)	(0.514)
Organic farms	-26.000*	1.786	-82.930
	(13.280)	(28.980)	(63.300)
Diversification	-1.932	-10.240	-0.369
	(41.410)	(45.480)	(26.960)
Year-NUTS2 fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	377	377	377
R2	0.35	0.38	0.35

Table A4 - Estimation results with coefficients – regional sample.

	Apulia		
	Gross Sale Production (1)	*Value Added (2)*	*Net Income (3)*
Collective supply	17.06	-20.84*	-27.71**
	(9.210)	(8.086)	(6.703)
Self-supply	13.75	-17.83*	-20.96**
	(7.280)	(7.550)	(7.361)
Sprinkler irrigation	-6.369	35.04***	37.09***
	(4.512)	(4.835)	(6.609)
Micro-irrigation	0.344	41.39***	47.35***
	(4.229)	(5.697)	(7.401)
Annual average temperature	81.87*	-39.77	-79.10
	(38.25)	(74.05)	(69.66)
Annual average precipitation	0.180	-0.116	-0.202
	(0.0878)	(0.171)	(0.158)
Utilised Agricultural Area	-2.916***	0.156	1.365*
	(0.224)	(0.328)	(0.570)
Number of workers	13.43***	1.096	-8.494
	(0.628)	(3.325)	(6.207)
CAP funds	0.000175	-0.000782***	-0.000766***
	(0.000107)	(8.29e-05)	(4.30e-05)
Water costs	-0.00252***	-0.000430	0.000430
	(0.000453)	(0.000662)	(0.000570)
Specialisation	1.009	1.620***	1.538***
	(0.509)	(0.261)	(0.0550)
Organic farms	-63.62***	-35.83***	-35.14***
	(9.640)	(5.622)	(0.926)
Diversification	-1.932	-10.240	-0.369
	(41.410)	(45.480)	(26.960)
Year-NUTS2 fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	147	147	147
R2	0.464	0.418	0.372

	Emilia-Romagna		
	Gross Sale Production (1)	*Value Added (2)*	*Net Income (3)*
Collective supply	-1.879	5.430	2.160
	(4.723)	(4.757)	(3.554)
Self-supply	-1.509	16.50	14.40*
	(5.185)	(10.03)	(7.541)
Sprinkler irrigation	4.460	-0.843	2.759
	(4.877)	(4.078)	(5.840)
Micro-irrigation	15.55	-2.729	-0.590
	(8.413)	(7.017)	(8.924)
Annual average temperature	-0.00851	0.00141	0.0154
	(0.0133)	(0.0455)	(0.0440)
Annual average precipitation	0.000109	0.000456*	0.000307
	(0.000136)	(0.000198)	(0.000181)
Utilised Agricultural Area	1.914***	2.143**	1.704**
	(0.188)	(0.701)	(0.729)
Number of workers	-7.865	-15.96*	-13.79*
	(7.487)	(8.246)	(6.925)
CAP funds	-0.000253	-0.000795	-0.000745
	(0.000531)	(0.000595)	(0.000435)
Water costs	-0.00257	-0.00657**	-0.00575***
	(0.00325)	(0.00254)	(0.00128)
Specialisation	1.755	2.202**	1.972
	(1.481)	(0.705)	(1.092)
Organic farms	-12.12	20.79	-112.0
	(13.36)	(29.48)	(93.30)
Diversification	6.298	-8.098	-4.439
	(36.45)	(34.89)	(22.70)
Year-NUTS2 fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	230	230	230
R2	0.339	0.410	0.369

Food price dynamics in Turkey's agricultural export market with selected machine learning approaches

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Abstract

Price fluctuations significantly impact supply and demand mechanisms, particularly in agriculture and food production. These effects are often persistent and challenging to adapt directly, making it crucial for agrarian countries to understand the factors driving these changes. This research focuses on calculating a specific food price index related to Turkish food exports, with the goal of evaluating the factors contributing to volatility in this index. Using data from 1991-2022, the analysis employed selected machine learning methodologies to project potential policy interventions. The support vector regression (SVR) predictions revealed that rising prices of exportable products are driven by various factors, including cost items, food price inflation, unemployment levels (as an indicator of income), and exchange rates. The predictions closely aligned with the actual calculated variables, suggesting that variations in aggregate price levels, exchange rates, and technology-related and import-dependent costs are critical for observation and evaluation. These factors appear to play a more significant role in determining price inflation for Turkish agricultural and food products.

Keywords: *Food trade, Food prices, Machine learning, Turkey.*

1. Introduction

Prices of goods and services are critical indicators of a country's economic well-being and societal welfare. Among these, food prices hold particular significance as they constitute a substantial component of aggregate price levels. The Food and Agriculture Organization (FAO) regularly announces food prices, providing a global benchmark that complements domestic price data or Consumer Price Index (CPI), a key measure of inflation that reflects the cost of living and purchasing power of a population. This bilateral relationship between food prices and CPI is well-documented, with evidence suggesting that food prices exert a stronger influence on CPI than other goods (Oral *et al.*, 2023).

Inflation in agricultural commodity prices often outpaces overall CPI, driven by rising input costs that significantly affect production

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outputs. This dual effect highlights the complexity of inflationary pressures in the agricultural sector (Canbay, 2023). The implications are particularly profound for countries like Turkey, where agriculture plays a vital role in both domestic consumption and international trade. Turkey is a significant producer of a wide range of agricultural products, including some tropical and sub-tropical items (Gunes *et al.*, 2017). The country's agricultural sector has evolved from traditional dry farming to more sophisticated irrigated and controlled production systems, which have enhanced its export potential (Yucer, 2020).

The impact of food and agricultural prices on macroeconomic stability is more pronounced in producer countries, where these goods serve as both consumer staples and commercial exportable products (Page, 2013). This dual role underscores the importance of understanding the factors driving price volatility. In recent years, numerous studies have examined the dynamics of food prices in Turkey, often focusing on the relationship between agricultural producer prices (PP) and CPI. For instance, Canbay (2023) conducted a panel causality analysis across selected developing economies, including Brazil, India, Indonesia, Turkey, and South Africa. The study found that in Turkey, rising agricultural prices contribute to higher consumer prices, while inflation tends to suppress agricultural prices. Interestingly, the study revealed diverse impacts across other countries, highlighting the complex interplay between inflation and agricultural prices globally.

Further investigations into Turkey's food price deviations, spanning data from 1992 to 2022, have employed various quantitative methods. For example, Ozcan (2023) utilized Augmented Dickey-Fuller (ADF) tests to assess price bubbles in datasets from the FAO, OECD, and IMF, identifying significant deviations in FAO and IMF datasets. Meanwhile, Ozdurak (2021) explored the interplay between Turkey's national agricultural price index, the FAO index, and exchange rates from 2000 to 2020 using a Vector Autoregression (VAR) approach. The findings indicated that domestic price increases have a more substantial impact on the FAO index, while short-term exchange rate depreciations negatively influence agricultural imports.

Given the importance of these findings, this study aims to detect and analyze variations in Turkey's food prices from 1991 to 2022, with a particular focus on exportable agricultural products. By employing alternative machine learning methodologies, this research seeks to investigate the effects of macroeconomic and global factors on food price volatility, offering new insights that could inform policy interventions and economic strategies.

2. Methodology

Inflation in agricultural and food commodity prices has been closely monitored through announcements by national statistical organizations and global entities such as the FAO. This research aimed to develop a unique index specifically for exportable agricultural products of Turkey. The food price index was adjusted based on the export proportions of various product groups, including cereals, meat and dairy products, oil products, and sugar. Subsequently, the variation in this index was analyzed in relation to several macroeconomic factors, including the FAO's Food Price Index for Turkey (FFPI). Other influential factors considered in this research included macroeconomic cost data and global economic indicators. The analysis spanned a 31-year period from 1991 to 2022.

The Food Price Index specific to Turkey (FPT) was developed using a formula that incorporates data on exportable food products and their respective prices:

(1) $FPT = \sum \{a_i/b_j*(P_i/P_j)\}$

a_i= the export share of product i in the relevant product group j

b_j= the export share of product group j in the total agricultural and food exports

P_i= the price index of product i

P_j = the price index of the product group that the product takes place in.

Product groups (j) and products (i) used to calculate the index for Turkey was as following due to FAO databases.

Cereal	*Meat*	*Milk*	*Oil Products*	*Sugar*
• Wheat • Barley • Maize • Millet • Oat • Rye • Sorghum • Rice	• Cattle: bone – without bone – fresh – frozen chilled • Buffalo – beef • Turkey meat • Sheep (sheep + chilled/ frozen • Chicken	• Raw milk – cattle • Raw milk – cow; condensed + operated: raw buffalo milk + butter + cheese • Sheep – cream	• Groundnut • Olive • Maize • Soya • Sunflower • Sesame • Cotton seed • Safflower	• Sugar beet

Therefore, this weighted index enabled is an indicator reflecting the shares of Turkish exportable agricultural products. The specific calculated export based FPT (y_i) for Turkey was run against the following variables (x_i):

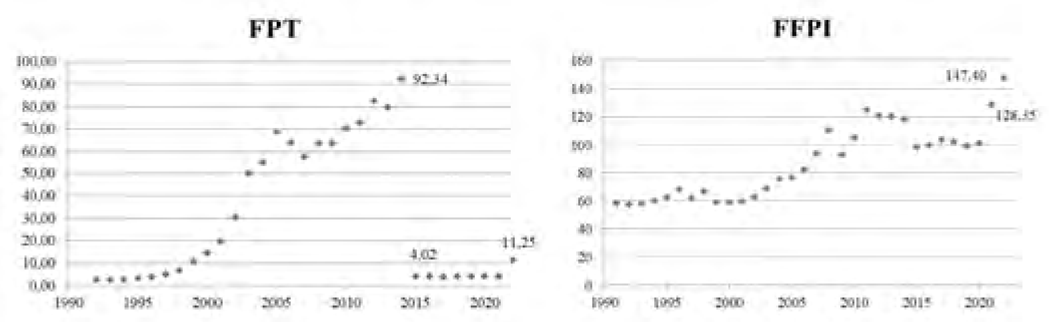
- Food Price Index announced by TUIK for Turkey – PPF_TR
- Producer Price Indices (TUIK)
  a) Petroleum and Gas Prices – PGP
  b) Agricultural Machinery Prices – AMP
- Share of People Employed (%) (ILO) – R_EMP
- Number of People Unemployed (thousands) (ILO) – UNEMP
- Exchange Rate (Dollar/ TL) – EXC
- FAO Food Price Index – (FAO) – FFPI

Prior to the analysis, the calculated export-based index that is the dependent variable (FPT), and the announced FPI for Turkey (FFPI) were demonstrated in the Figure 1.

The continuously rising food prices are evident on the right-hand side of the data, but a sharp decline in the calculated index after 2014 warrants attention, particularly in relation to agricultural exports. Over the 31-year period, the index for exportable products increased in 22 years. The fluctuation in the Food Price Index (FPT) between 2004 and 2008 seems to correlate with rising imports of agricultural products and inputs, reflecting the varying significance of these products within the FPT index (Anonymous, 2008). The observed fall in 2014, followed by a subsequent stabilization, also appears to be linked to import patterns (Orkunoglu Sahin, 2022). As a result, rising food commodity prices contributed to a reduction in exports.

Despite the declining trend in many segments of exportable products, demand for major crops such as cereals and vegetables in Turkey increased, influencing agricultural prices and price indices. The FAO index for Turkey rose by 15%

Figure 1 - Calculated Index (FPT) and FAO Index for Turkey (FFPI) (1991-2022).



Source: Authors' calculation and findings based on FAO (2022) and TUIK (2022) datasets.

from 2021 to 2022 and by 46% from 2020 to 2022. Particularly the COVID-19 pandemic led to an increase in exports for Turkey in 2021 and 2022, following the elimination of trade barriers imposed during the early stages of the pandemic and bolstered by increased producer support (Altay, 2024). Given these trends, this study aimed to analyze the variations using machine learning methodologies. To differentiate data projection tasks in analytics, machine learning methodologies such as multiple linear regression (MLR), support vector regression (SVR), and artificial neural networks (ANN) were employed.

Firstly, multiple linear regression (MLR) methodology derived from Gaussian analytical perspective focuses on finding a linear equation of potentially effective factors (x_i) which provides estimates that are close to the real values of the dependent variable (y_i) as shown below (Sheynin, 1999).

$$f(x_i) = y_i = \sum \beta_i * x_i + u_i$$

Food price index is the dependent variable in our case. The proximity of estimates to observed/real values of y_i is measured with the sum of squared errors ($\sum u_i^2$) of estimation in the econometric literature (Narula and Wellington, 1977). With minimum deviation, the probability of finding a more explanatory linear relationship between variables and increasing the accuracy of the estimates and forecasts of the economic data becomes more eligible. In other words, minimum errors mean maximum proximity between estimated and calculated food price indices.

In accordance with recent statistical progress, the regression methodology was implemented by dividing the sample into training and testing sets, consistent with MLR and machine learning practices. Train and test approach refers to learning the data tendencies from a randomly separated portion/percentage of the available dataset and forecasting the relationship with the remaining observations. With training the data, the probability of minimizing the sum of squared errors increases. Wide deviations can be removed with training and reaching robust and consistent estimates with higher fit of regression becomes more eligible (Dietterich, 1995). Additionally, overfitting reduces as the data is processed more than once to eliminate extreme values (Allgaier and Pryss, 2024). Besides, more training can be suggested for larger dataset as testing sample would be large enough to capture the unseen projections. More testing is more efficient for smaller datasets and mostly 80-20% of train-test-split approach is being used in the literature (Manda *et al.*, 2021).

Secondly, support vector regression (SVR) model predicts the weights of input components (w) of the estimation vector (x_i) that affect corresponding output (y_i).

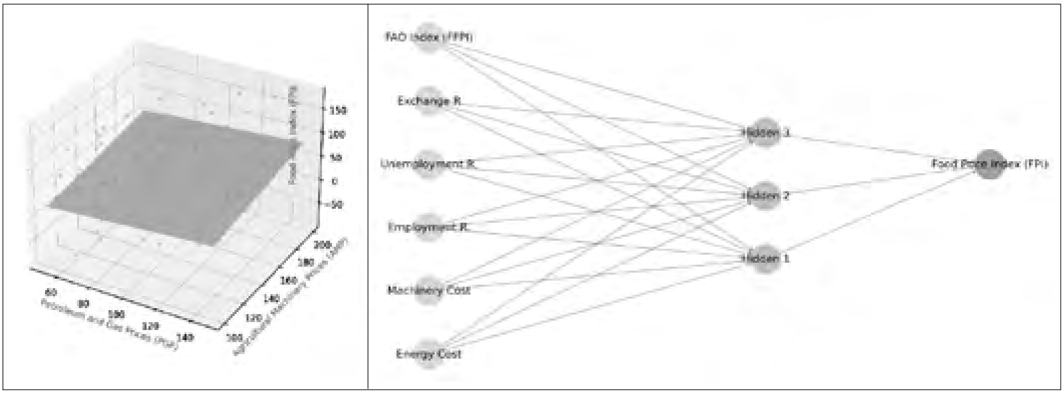
$$f(x_i) = y_i = \sum w * x_i + b$$

SVR was introduced mostly to solve non-linear problems with regression (Montesinos López e*t al.,* 2022) and it is an extension of SVM (support vector machine) that has been used for non-linear classification since its introduction for computer science algorithms (Cortes and Vapnik, 1995). The objective of SVR is again minimization of the errors, but differentiating feature is using a hyperplane and elimination of the commonalities in the error terms (Beniwal *et al.*, 2023). Hyperplane is the line, plane or more than 3D spaces that differentiates data depending on the number of factors or inputs explaining the expected food price index (y_i).

SVR does not enforce linear process and look for a kernel that guarantees the optimization rather than minimization (Jayaswara *et al.*, 2023). The supervised machine learning algorithm classifies without using default hyperparameters and uses a kernel function for forecasting (Awad and Khanna, 2015). Kernel function enables analysis of non-linear data and inference on multi-dimensional problems. It can be classified as linear, polynomial, radial basis function (RBF) and sigmoid kernel. RBF kernel helps trial of different non-linear scenarios to find the best fitting equation. Sigmoid functions are more alike neural network implementations. Mostly, RBF kernel is used to interpret data with more than two dimensions or with at least 3D hyperplanes (Cortes, and Vapnik, 1995; Simian *et al.*, 2020).

Thirdly, artificial neural network (ANN) approach is used to forecast potential networks between inputs that yield the best fit for the out-

Figure 2 - Demonstration of SVR hyperplane (a) and ANN relationships between input and output layers (b).



put with a revealing approach regarding hidden layers of input correlations (Najem et al. 2024). The hidden layers are the non-described and invisible factors affecting the neural relationship between inputs and outputs. In other words, there are factors that were not defined prior to the analysis, and ANN approach aims to portray these factors and their relationship with both sides of the equation meaning inputs and outputs. The number of layers is related to the complexity of the relationship and dimensions of the question (Siddique Afraaz and Vijayaramachandran, 2020). The networking approach suitable for machine learning was developed within a stock price prediction study conducted for Shanghai Stock exchange (Wen *et al.*, 2024).

Therefore, three Machine Learning methodologies explained technically above were used in this research to estimate and predict the factorial relationship that provides information on food price index (FPT) calculated for Turkey. Interpretation of price changes with recently used approaches appeared as a complementary objective for the current research. The analyses were conducted in Python Anaconda Ide. The ratios for training and testing the data were 80% and 20% respectively for all methodologies.

To summarize, the major difference between these algorithms is the dimension of the estimated food price index and processing of the data. The multi-variables are used to estimate a linear relationship and show a linear graph of findings in MLR. The relationship lay-out of SVR and ANN processes are demonstrated below.

In SVR, more dimensions are included for multi-variables, and a hyperplane is estimated. In ANN prediction, available – measured inputs are weighted with different approaches and additional invisible algorithms are produced to reach the single output, the food price index. Estimation and predictions of three algorithms were demonstrated in the following section.

3. Results

3.1. *Multiple Linear Regression Results (MLR)*

MLR was implemented alongside machine learning algorithms. Initially, the factors were estimated at their original levels. However, the anticipated multicollinearity between variables was assessed using Variance Inflation Factors (VIF) following the level estimation. The results in Table 1 indicated that the VIF values for all variables were notably high, with agricultural

Table 1 - VIF of independent variables.

Variables	*PPF_TR*	*PGP*	*AMP*	*EXC*	*UNEMP*	*R_EMP*	*FFPI*
VIF	794.39	89.14	1,364.97	115.09	123.76	90.41	58.81

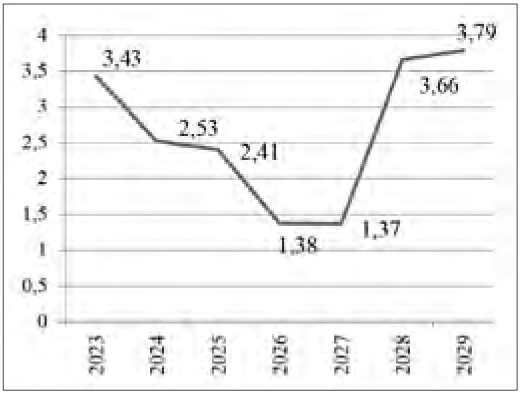
Source: Authors' calculation and findings based on FAO (2022) and TUIK (2022) datasets.

machinery prices being the most non-linear variable, followed by the FAO index for Turkey, the unemployment rate, and exchange rates.

Before applying linear adaptation, the data was initially estimated with a moderate R^2 of 79%, but the Mean Squared Error (MSE) was 261.96 and this indicated a low fit. The VIF values remained high even after logarithmic transformation, necessitating a reduction in variables for more accurate projection. Consequently, multicollinearity among the variables was not sufficiently addressed through linear transformation alone, prompting the consideration of additional methods. Lasso and Ridge regularizations were proposed to mitigate multicollinearity. The transformed logarithmic variables were estimated using Ridge modification, with a reduction in highly collinear variables, such as the announced Food Price Index (PPF_TR) and the share of employment (R_EMP). Ridge regression constrains the sum of squares of the parameters, minimizing the likelihood of an L2 penalty (Thevaraja *et al.*, 2019). The goodness of fit for this log-ridge estimation improved to 80%, and the MSE was reduced to 0.36. An antilog calculation to infer odds ratios revealed that the highest contributors to the export-based index (FPT) were the announced prices and the agricultural machinery price index.

Following Ridge modeling, Lasso regularization was implemented. Lasso drives the ineffective parameter estimates to zero, whereas Ridge regression allows for the interpretation of all variables by distributing the collinearity effect among factors (Yang and Wen, 2018). The change in the export-based FPT was most significantly influenced by agricultural machinery prices, with an estimated impact of 1.77, followed by exchange rates. However, the rising exchange rate resulted in a relatively smaller increase in the index, with an odds ratio of 0.28.

Figure 3 - MLR – Ridge Predictions for FPT (2023-2029).



Source: Authors' calculation and findings based on FAO (2022) and TUIK (2022) datasets.

The fit of this estimation was 63%, with an MSE of 0.68. These estimates suggest that MLR-RIDGE may be a more effective approach. Accordingly, the FPT was projected for the next seven years using MLR-RIDGE estimates and demonstrated in Figure 3.

The calculated index was 11.25 in 2021 and decreased to 4.82 in 2022. Based on these reference figures, the decline is expected to continue until 2028. However, the reduction in exports does not appear to support a rising index within the current methodology. In other words, there is no short-term expectation for a significant increase in the index. This does not imply that prices will decrease; rather, prices are expected to continue rising, but at a slower pace.

3.2. *Support Vector Regression Prediction (SVR)*

SVR was implemented for level and log-transformed versions of the factors. Kernels of estimation were linear and radial basis function (RBF) for level and polynomial kernel was

Table 2 - SVR Results for FPT estimation.

	LEVEL		*LOG*		
	LINEAR	*RBF*	*LINEAR*	*RBF*	*POLY*
MSE	3 545	1 333.26	0.97	0.28	1.56
R^2	-1.78	-0.05	0.47	0.85	0.15

Source: Authors' calculation and findings based on FAO (2022) and TUIK (2022) datasets.

added for the logarithmic estimation. The R^2 and MSE comparisons of initial modelling were demonstrated below. The constant of the prediction was taken as 10.

The RBF kernel mostly produces smooth and flexible regression curves for multidimensional data that adapt well to the training data with lower MSE and higher R^2 (Cortes, and Vapnik, 1995). Besides, negative R^2 of level estimations directly sign improper fit of the model. The best inference could be made with RBF kernel estimation of SVR modelling with log-transformation. The fit of predictions can be evaluated by the graphical representation. The overlap between the calculated export-based index and the predicted FPT is evident in Figure 4.

Figure 4 - Fit of SVR – RBF predictions (2016-2022).

Source: Authors' calculation and findings based on FAO (2022) and TUIK (2022) datasets.

The average difference between the actual and predicted values over the tested 7 years is -0.29, with a mean squared error of 0.28 as indicated in Table 2. This suggests a slight depreciation in the calculated food index anticipated for the future. Given that the radial basis function aims to minimize the differences between real and predicted values, it can be concluded that the predictions are compatible with the actual values.

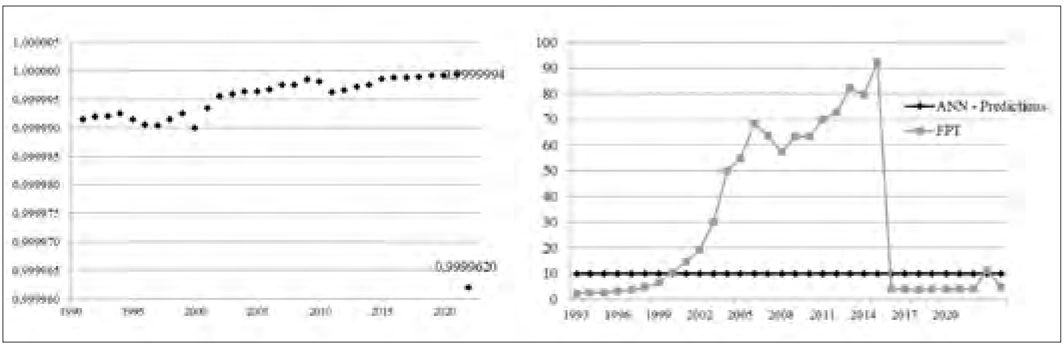
3.3. *Artificial Neural Networks Prediction (ANN)*

The reduced model was employed to determine if there is a neural relationship between the inputs and outputs. With two independent variables, the non-linear model was structured with three layers and one output. The predictions aligned well with the log-transformed data. As the model underwent repeated training, the fit of the data improved. The number of training cycles was set at 10,000 epochs, due to the limited sample size of 32 years. If the sample for the secondary data was large enough or pre-trained data was utilized, the number of trials to converge might be smaller (Zhang *et al.*, 2017). This approach suggests repeated training for higher fit without overfitting the estimates (Maliar *et al.*, 2021).

The predictions indicate a compatible index between 9 and 10 over the past 31 years, as shown on the left pane of Figure 5.

The calculated FPT and ANN predictions were closely aligned between 1991 and 2000, with a similar proximity observed after 2014. These periods of adjustment correspond to rising exports and the existing capacity to meet domestic demand. However, significant variation was noted during the first decade of the 2000s.

Figure 5 - ANN Predictions and FPT for 1991-2022.



Source: Authors' calculation and findings based on FAO (2022) and TUIK (2022) datasets.

Given the outputs, predictions for the future are better aligned with SVR and ANN models for estimating the specific export-based Food Price Index on an annual basis.

4. Discussion

Energy use is an integral part of agricultural production. Both the costs of production and agricultural value added are affected by the energy price volatility globally. This is especially valid for importing countries as machinery costs rise in a cyclical manner (Beckmann *et al*., 2020). Rising energy use appeared to affect agricultural production positively, while the energy cost had negative impact due to 1971 and 2003 annual data for Turkey (Karkacier *et al.*, 2006). As a significant supplier, oil price shocks used to stimulate industrial production in Iran. However, agricultural production had reduced, calling for more imports due to quarterly measures between 1989 and 2006 (Farzanegan and Markwardt, 2009).

Research on the economic impact of energy costs in BRICS countries portrayed that rising oil prices and sudden shocks increases marginal cost of production and reduces productive capacities of countries that are dependent on energy imports (*Nasir et al*., 2018). Accordingly, oil importing China and India have been worse off with rising prices, while exporters Russia and Brazil experienced rising export revenues in exchange of rising local production costs, the former being more significant. The impacts of international financial fluctuations on spot prices of wheat were analysed for Egypt between 1998 and 2017 (Ahmed, 2021). The research portrayed the uprising impact of futures prices in Paris (CBOT) and USA (MATIF) markets on prices of Egyptian wheat market, which is import-dependent.

In a complementary way, the reasoning behind rising production costs is related to changing availability and costs of financial inputs. Not surprisingly, the financial volatility is related to national currency volatility. Depreciating Chinese Wuan led to rising costs of energy inputs and this indeed led to rising interest rates and rising aggregate production costs in every economic activity line (Kim *et al.*, 2017). With a different perspective, unavailability of resources accompanied with low awareness and extensive information poses risks for importing countries as many African countries. An example is from Tunisia, with limited water and technological inputs and market instability due to international dependency (Thabet *et al*., 2024). The negative impact of strict Tunisian currency devaluation on prices has also been visible after 2012. The research suggests promotion of smart agriculture and reduction of import dependency. Additionally, insurance and post-harvest management systems need to be promoted among Tunisian farmers.

It is also essential to evaluate the changing costs and depreciating Turkish Lira and their multiple effects. Although cost items generally drive-up prices in economic terms, the technology-related costs examined here were largely mitigated by the negative impact of the appreciating Dollar against Turkish Lira. The depreciation of currency and the associated increase in exports resulted in variations in the calculated and predicted indices over the study period. Therefore, the index formed based on exportable products was more affected by exchange rate fluctuations, while the indirect impact of exchange rates on energy and machinery costs was less significant. This also can be related to import dependency for other inputs as well. The rising costs observed in 2020 and 2021 were consistent with the increasing price indices used in the study.

The predictions confirmed a continuous fall in the export-based index from 2016 to 2019, followed by a sharp increase. The index more than doubled between 2020 and 2021, rising by 143%, with a further 20% increase from 2021 to 2022. These inverse shifts are attributable to the COVID-19 pandemic, as observed globally, and to exchange rate fluctuations specific to Turkey. The variations in the predictions, calculated values, and FAO-announced figures were consistent throughout the sample, reflecting both country-specific and global factors.

The predicted index variations can be viewed as a reflection of Turkey’s experience during the COVID-19 pandemic. Major impacts on food markets included supply chain disruptions and trade interruptions, which affected prices, as confirmed in recent studies (Kubatko *et al.*, 2023). Similar effects have been observed in other countries, including the USA and Canada, highlighting the global nature of the pandemic's impact (Alabi and Ngwenyama, 2023). In Australia, primary data research revealed significant increases in the costs and prices of healthy nutrition, including fresh products, since 2019 (Lewis *et al.*, 2023). Recent findings for Turkey also underscore the impact of COVID-19, as well as other challenges such as oil price fluctuations and export conditions related to the Russian - Ukrainian conflict (Urak, 2023).

Rising food prices in response to external factors are a significant contributor to these fluctuations. FAO-announced food prices, which indicate food price inflation, appeared to increase the export-based index. The expected bilateral relationship between inflation and prices was evident. Alongside rising prices, the reduction in food exports since 2014 can be seen as a contributing factor to the fall in the index. This global trend has had a more pronounced effect on countries like Turkey. In an evaluation of Turkish-Chinese exports, both countries reported rising prices, increasing costs, and declining exports (Kazancoglu *et al.*, 2023). However, the fall in exports since 2014 is more closely linked to rising costs and an insufficient or declining supply of the major products examined in this study. Additionally, the stable exchange rate before 2013 stimulated agro-food imports, and this effect seems to have persisted amid global challenges (Ozdurak, 2023).

5. Conclusion

The study aimed to uncover the relationship between agricultural and food price determinants and a specific export-based index for Turkey. The calculated index, representing key exportable products and product groups, was evaluated against various production and trade-related factors. Using machine learning approaches, particularly Support Vector Regression (SVR), the model effectively captured 31 years of data. Significant correlations were identified between the specific food price index and input costs, such as energy and machinery, as well as exchange rates, which were negatively correlated with the index. Conversely, the index was found to rise in tandem with the unemployment rate and FAO-announced scores. This indicates that while rising technical costs and an appreciating Dollar tend to reduce food prices, increased unemployment or declining income levels lead to higher prices.

It is crucial to pre-evaluate the potential effects of macroeconomic challenges on agricultural production and pricing mechanisms. To better understand these effects, further research is needed, both on a comparative basis and through primary responses from producers. It is also important to consider the effects of exchange rates, unemployment, and income levels on agricultural and food commodity prices. While reducing demand inflation may not directly lower product prices, cost inflation has been more significant in agro-economic markets, impacting prices for end consumers. Since prices also influence economic growth through inflation, multidimensional policymaking and support mechanisms are necessary for Turkey and comparable countries. Although direct intervention in prices may be challenging, managing costs through effective investment in agricultural technology and inputs is essential. This conclusion is supported by the stronger effect of cost inflation on aggregate prices and using alternative evaluation approaches.

Specific inferences for Turkey are related to information and support mechanisms rather than direct market interventions. For critical products the public authority imposes minimum prices to protect both sides of the internal market. But these direct interventions are limited to products like wheat, hazelnut, tea and tobacco. A rising import-dependency is observed for wheat. Therefore, it is aimed to support reduction import dependency for wheat, while subsidization of remaining products mostly aims to protect export-competitiveness. Although it is not possible to support every single actor, public authorities have utilized other sorts of support with extension activities. There are significant funding tools available for producers and their unions. Ministry of Industry and Technology offers specific funding opportunities to small and medium sized enterprises and supports integration of smallholder actors. The farmers and other relevant agricultural operators also have direct funding opportunities provided by the Development Agencies. The major challenge here is reaching information rather than its availability. The organization of operators has been developing sincerely. However, reaching small units and assisting them at least towards cost efficiency need to be empowered. The extension officers are approved and monitored by the Ministry of Agriculture and Forestry. The ministry supports the producer unions, boards of agriculture and supra-structures of these NGOs to employ and monitor extension officers with further emphasis since 2010.

The two sides of agricultural trade are all effective in Turkish farm input and export product markets. The need to adjust import prices and at least maintain export revenues are attached to financial monitoring and guidance. All operators need to be informed on this extent as well. There it seems that empowerment of information systems is more essential under volatile conditions and these operators, especially the sector representatives, need to be supported in information dissemination processes.

These interpretations relying on technical findings can be extended to different sources of products or product group-based analyses can be streamed to use efficiency of techniques. However, it is important to keep in mind that the agricultural operators need to be informed about future economic expectations related to the awaited exchange rate fluctuations and input prices. These findings also emphasized that future projections on inflationary fluctuations are essential for production planning. Accordingly, the need for more focused index-based studies and dissemination of their findings are essential for assuring supplies.

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Notes

The international olive sector: challenges in the face of climate change

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A living testimony to the ancient and contemporary history of civilisations, olive growing continues to attract growing interest, driven by its social, economic and environmental dimensions. Able to adapt to a wide range of climatic and soil conditions, olive trees now cover almost 11 million hectares. Predominantly present in the Mediterranean basin, where it accounts for almost 80% of olive groves, it has gradually crossed its traditional borders to establish itself across the world: from California and South America (Argentina, Uruguay, Peru, Chile) to Australia or India, and as far afield as China.

In terms of international trade, almost a third of the world's olive oil resources are traded. World olive oil production is on an upward trend, despite inter-annual variations. It rose from an average of 2.1 million tonnes in the 1990s to 3.1 million tonnes in 2010, an increase of 48%, before levelling off. After two crop years that produced below average yield levels, the current crop year has seen a rebound to almost 3.4 million tonnes. This variability, which is largely due to the increased frequency of droughts, has been accompanied by an unprecedented rise in prices.

The expansion of markets beyond the Mediterranean basin has led to a sharp rise in olive oil exports, from 400,000 tonnes in the 1990s to over a million tonnes in recent years. Imports are following a similar trend. In the current year, seven markets account for around 80% of world imports of olive oils and virgin olive oils: the United States (35%), the European Union (17%), Brazil (8%), Japan (6%), Canada (5%), China (4%) and Australia (3%).

Considered a pillar of the Mediterranean diet, olive oil is distinguished by its high oleic acid and polyphenol content, endowing it with significant anti-inflammatory and antioxidant properties. According to numerous scientific studies, these characteristics contribute to the protective effects of the Mediterranean diet on cardiovascular health and have largely contributed to the expansion of its consumption worldwide.

The producer countries remain the main consumers of olive oil. Italy consumes 30% and Spain 20% of world production. The European Union remains the leading consumer market, accounting for 71% of global demand. The United States, with 8%, is following a steady upward trend, becoming a strategic market with great potential, especially as it imports almost all of its consumption. However, the emergence of new producer countries raises questions regarding their ability to compete with the sector's two historic leaders.

Climate change is increasing the frequency of extreme weather events, particularly in the Mediterranean basin, which has been identified as a climate hotspot. Drought, desertification and water scarcity are affecting olive growing and compromising yields. At the same time, new diseases and pests are emerging, such as verticillium wilt, the olive fly or the *Xylella fastidiosa* bacterium, threatening the sustainability of traditional olive groves.

Yet the olive tree is also recognised as an ally in the fight against climate change. Resilient, adaptive and able to survive in difficult conditions, it is the most widely cultivated woody species in the world and acts as an effective carbon sink. Its contribution to sustainability is based on the dual principles of adaptation and resilience. Technological innovations and developments in cultivation techniques now offer ways of optimising resources, particularly water, while increasing productivity. This has encouraged the development of intensively cultivated olive groves, particularly in Spain, Portugal and Italy, and, more recently, in Türkiye, Morocco and Tunisia, with the adoption of better adapted varieties and the mechanisation of operations.

The International Olive Council recently launched an initiative to assess the olive tree's potential access to voluntary carbon credit markets, consolidating its role as a strategic crop in the face of climate change. At a time when the international community is moving towards carbon neutrality by 2050, this initiative should be encouraged and supported in order to strengthen its feasibility and credibility.

Faced with these challenges, a renewed dialogue on the future of olive oil is essential. Its role as a vector for virtuous agricultural practices and environmental sustainability makes it a key sector for the years to come. This vision must be based on three fundamental pillars:

1. Produce more, sustainably, in a globalised world by facilitating trade, defending quality and authenticity standards, and protecting consumers;
2. Promote olive oil's unique contribution to human health;
3. Value its role in global health, to ensure the sustainability of the sector and the preservation of biodiversity.

The future of olive growing lies in its ability to combine tradition and innovation, local resilience and global dynamics. Faced with the climatic, nutritional and economic challenges of the 21st century, the olive tree is a powerful symbol of continuity and adaptation. Strengthening collective efforts to support this strategic sector, at the intersection of science, culture and the environment, is an imperative for the years to come.

NEW MEDIT

Scope

New Medit is an international open access journal published quarterly on behalf of CIHEAM.
The Journal seeks to act as a bridge between the relevant regional studies to enhance regional cooperation and sustainable development, by providing a platform for theoretical and empirical debate in the fields of social and economic sciences, regional development and environmental studies in the Mediterranean Region.
The main subjects of interest include the economic and social transformations in Mediterranean Countries in particular agro-food economics, rural development, environmental economics and sustainability issues around all Mediterranean region.
New Medit welcomes studies tackling the various problems characterising the economy and agribusiness of Mediterranean countries with a multi-disciplinary approach and from diverse theoretical perspectives.

Types of article

New Medit publishes *Research/Themes* papers and *Notes/Reports*. *Research/Themes papers* include original essays and cutting-edge research closely related to the aims and scope of the Journal. *Notes/Reports* include comments or studies on singles experiences which aim to facilitate the debate and dissemination of the real questions among the different territorial areas of the Mediterranean.
The journal operates with a double-blind peer review policy.
Papers are published in English or in French, with an abstract in English.

Guidelines

https://newmedit.ciheam.org

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