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# Regional Patterns of Pesticide Consumption Determinants in the European Union

**Raluca Georgiana Robu *, Ana-Maria Holobiuc, Alina Petronela Alexoaei, Valentin Cojanu and Dumitru Miron**

Department of International Business and Economics, Bucharest University of Economic Studies, 010374 Bucharest, Romania
* Correspondence: raluca.robu@rei.ase.ro

**Abstract:** This article contributes to the discussion about the socioeconomic factors that reinforce pesticide dependence in the European Union and hinder the transition to more sustainable agricultural practices in light of the European Union's Green Deal objective of reducing the use of pesticides by 50% by 2030. The analysis has a two-pronged purpose: (1) to identify the determinants of pesticide consumption in the European Union by conducting a set of four seemingly unrelated regressions and (2) to emphasize the existence of regional patterns across EU countries formed by the factors that significantly impact pesticide consumption based on a cluster analysis. Per capita GDP, selling prices, population, and real income positively influence pesticide use, whereas subsidies and organic agricultural area negatively influence them. Pesticide use is most affected by GDP per capita and least affected by subsidies. Cluster analysis highlights regional differences reflected in three clusters: (1) the most recent EU member states, (2) the European countries with large population levels, and (3) the countries with the highest GDP per capita. Our findings may contribute to the EU's capacity to generate policy changes at the member state level and can be built into recommendations to address the persistent overuse of pesticides.

**Keywords:** Green Deal; Farm-to-Fork; pesticides; sustainable crop production; sustainable production policies



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## 1. Introduction

The term 'sustainability' in agriculture describes the need to meet the food needs of the growing human population while ensuring minimal impact on the environment and people as well as profitability for producers [1]. Most researchers agree that sustainability in the agricultural field should, by definition, address the environmental, economic, and social issues associated with its practice [2]. Food systems refer to the entire range of activities from production to consumption [3] that contain the 'environment, people, inputs, processes, infrastructures, institutions' and the 'socioeconomic and environmental outcomes' [4]. They are widely spread across multiple economic territories in various geographic regions, a fact that leaves them exposed to various risks [5]. The growing demand for food, which mainly comes from the growing population, simultaneously exerts pressures to keep food prices affordable to all people which is opposed by pressure to keep the businesses of agri-food producers profitable and address climate change issues. These pressures impact food systems at an unprecedented level and emphasize the need for sustainability. Furthermore, prices for agri-food inputs and outputs have increased significantly in recent years because of the COVID-19 pandemic and the war in Ukraine; these events have caused severe shortages in the supply chain [6,7].

Contrary forces are at work when attempting to ensure the sustainability of agriculture. Several agricultural practices that are employed to ensure that food is affordable and available to the growing population, while also generating enough revenue for farmers to maintain agricultural production, have a detrimental effect on both human health and the environment. According to the European Environment Agency, most of the existing operations of the EU agri-food systems have a direct impact on the deterioration of the environment and climate in Europe. These activities also have a negative impact on biodiversity and climate change and cause pollution [4]. Various pesticides on the market have been banned because of their extremely severe effects on both human health and the environment; other available pesticides are fake. Pesticides that are used legally may also cause diseases of different types and intensity levels [8]. Estimates indicate that there are 168,000 deaths worldwide and one to two million cases of pesticide poisoning each year [8].

Fertilizers and pesticides are the two types of chemicals that are widely used in current agricultural systems. The former increase soil fertility, allowing crops to produce higher yields, while the latter protect crops from diseases and pests [9]. Therefore, the use of pesticides in agriculture, along with other measures, has positive effects on the level of crop production. Production per unit of input is often referred to as intensity in agriculture [10]. Higher intensity can be obtained mainly through mechanization [11], improved seed productivity [12], reduced crop cycle, increased fertilizer consumption [13,14], and reduced losses due to the use of pesticides [15].

The Common Agricultural Policy (CAP) had a major contribution to agriculture intensification [16,17], providing incentives to farmers to increase productivity. The drawback, which was later acknowledged, is that agriculture intensification further degrades the soil, decreasing the concentration of organic resources [18,19], thus increasing the need for additional compensation. Current food support policies do not meet the requirements of a modern food system and have not kept up with the rapid structural changes that affect food systems or the difficulties caused by these changes [20]. Market price support, production payments, and the unrestricted use of inputs are among the most distorting government interventions and the most environmentally damaging agricultural support programs. They create incentives for increased input consumption, for the allocation of land to subsidized crops, and for the introduction of additional land for agricultural production. In the absence of adequate limitations, payments based on variable inputs could encourage the overuse of pesticides, resulting in significant damage to freshwater ecosystems and biodiversity [20].

Against the backdrop of growing concerns around the impact of pesticide use on human health and the environment, many sectoral policies address the current status of agriculture and biodiversity in Europe, encourage a systemic approach to the sustainability of the agriculture and food sector, and outline the primary objectives centred on sustainability. By 2030, the Green Deal, Farm-to-Fork, and biodiversity programs hope to reduce the loss of nutrients from both mineral and organic fertilizers by at least 50%, while ensuring that soil fertility does not deteriorate in the process. This ambitious target, along with other EU objectives, such as reaching 25% organic agriculture, is expected to result in a reduction in pesticide use. The use of organic farming is generally minimal or non-existent [21]. However, many aspects are likely to be contentious, given the dispute over the production impacts of all new regulations. A macrolevel assessment based on the Green Deal objectives (that is, 50% reduction in overall pesticide use and risks, 50% reduction in more hazardous pesticides, 20% reduction in fertiliser use, 10% of agricultural land under organic production), concluded that the Farm-to-Fork and biodiversity strategies will result in a 'decrease of the volumes produced per crop in the entire EU on average ranging from 10 to 20%' and prices for some crops (for example, wine, olives and hops) will increase. As a result, exports of EU crops will fall, while imports will increase (the volume of imports of products can double) [22].

Throughout the EU, agri-food systems differ significantly and their progress in terms of sustainable development is strongly influenced by these differences. According to [23], pesticide sales between 2011 and 2020 emphasise substantial regional differences in both the absolute amount of pesticides used (per hectare of agricultural land) and in total sales. Sales have increased on the markets of certain member states (for example, Latvia, Austria, Germany, France, and Hungary) and fell in others (for example, Czech Republic, Portugal, Denmark, Romania, Belgium, Ireland, Italy, Sweden, Slovenia, Netherlands, and Cyprus). The difficulty of setting national targets in CAP national strategic plans (in this case, for the use of pesticides) is increased because there are differences in both national evolutions and absolute quantities of pesticides (per hectare of agricultural land and overall). This applies to all quantitative targets of the Green Deal currently specified at the EU level [24]. Although member states are required to adopt legally binding targets for the achievement of the overall EU targets, in regard to determining national targets, members have the flexibility to take into account their own national circumstances, including their level of pesticide use and their historical level of progress.

This article aims to serve as a starting point to reveal the socio-economic and political factors that reinforce pesticide dependence in the European Union and determine the slow pace in the transition to more sustainable agricultural practices. The analysis is narrowed to pesticide consumption since pesticides are the most widely used tool in intensive agriculture and because the European Green Deal includes more stringent reduction targets. The paper has two main objectives: (1) to identify pesticide consumption determinants in the European Union (EU) by running an empirical model based on panel data for EU27 between 2001 and 2019; and (2) to emphasize the existence of some regional patterns across EU countries and classify the EU27 member states into broad categories according to the factors that had been shown to significantly affect pesticide consumption. By achieving these objectives, cluster characteristics can be developed into recommendations to combat the persistent overuse and reliance on chemical pesticides at regional levels.

Our findings may contribute to the EU's capacity to generate policy change at the member state level and may be useful to a wider audience interested in the restraints national states face in adapting their policies to meet the Grean Deal objectives. This paper contributes to the body of knowledge in three ways. First, it provides a comprehensive analysis of the multiple factors that contribute to pesticide use in agriculture, in contrast to the majority of existing studies that discuss pesticide consumption from either micro or macro-economic perspectives. Second, the article looks at the EU market and provides, for the first time, a cluster analysis applied to the determinants of pesticide use in agriculture. Lastly, the original elements of the paper reside in the complementarity between regression and cluster analysis, with the purpose of determining common regional patterns for member states. The article is structured as follows: Section 2 presents a literature review on frequent determinants of pesticide consumption; Section 3 is dedicated to the methodological framework; Section 4 presents the findings of the regressions and the cluster analysis; and the last section brings together final observations and conclusions.

## 2. Review of the Scientific Literature

### *2.1. Determinants of the Use of Pesticides in Agriculture*

The section presents a review of the literature on the impact of various economic and social factors on the widespread use of pesticides in agricultural production and provides the scientific basis for the regression analysis.

Given the multifaceted and transdisciplinary nature of pesticide dependence, it is impossible to identify a rigorous review of generally accepted and standardized variables. Although a wide range of studies have sought social, economic, and political explanations, most of these studies have focused on a small number of factors or have approached the topic from a microlevel perspective and emphasize the role of farmer decision making [25–29]. To our knowledge, no analysis has been performed at the EU level on the determinants of pesticide use in agriculture. Most studies have addressed the environmental and health impact of pesticide use or have performed a comparative analysis of National Action Plans of member states [30–32]. One general observation from the literature reviews is that, while some research investigates the factors of pesticides and fertilizers together, others study them individually. The widespread use of pesticides among intensive agricultural tools and the larger reduction target outlined in the European Green Deal regulations required a focus on analysing the determinants of pesticide consumption. Depending on data collection possibilities, we tested the impact of several factors on the use of pesticides in European agricultural practices at country level, continuing with a cluster analysis to highlight possible geographical patterns of these determinants.

As described in the Introduction, the use of pesticides reduces crop losses and contributes to an increase in overall crop yield [33,34]. The primary factors that have caused an increase in agricultural productivity have deep roots and do not all operate in the same way under comparable conditions.

In the literature, the most cited determinant for the widespread use of pesticides is the growing demand for food from the growing population at the global level, which puts greater pressure on increasing crop yields and using resources more efficiently [35]. At the European level, between 1960 and 2020, the population has decreased overall, while net migration to Europe increased during the same period [36]. At the same time, trade liberalization offers opportunities for European farmers to supply foreign markets [37], especially from Eastern Europe [38,39]. To some, this reduces the relevance of the link between the population of a country and the pressure to use various methods that improve productivity. With these constraints, we will test the impact of the population on the use of pesticides in the same country.

Demand and production for food, in general, and for healthy food, more specifically, varies between countries, depending on the country's wealth. Economic development determines an inverse U-shaped evolution of the curve that describes the use of pesticides. The least developed countries have a small consumption of chemicals in agriculture because the prices of these inputs are prohibitive; developed countries are heavy users of pesticides, while the most developed countries use them more efficiently to increase production [40,41]. Ref. [42] observed an increase in the use of pesticides in the least developed countries as their trade connectivity with developed countries improves, resulting in increased imports of pesticides and increased exports of agricultural products. Ref. [43] found an increase in the market for organic products in rich countries in western Europe as they have a higher demand for healthy food. Using GDP per capita as the independent variable, our aim is to determine whether there is a causal relationship between economic growth and pesticide use based on the references mentioned above.

From a supply perspective, the available workforce in agriculture was reduced by the urbanization process [44] (later in the case of Eastern European countries), imposing the need for higher labour productivity. The issue of labour scarcity in agriculture has been partly diminished since 1990 by the migration of low-wage labour to rural areas either from the same country or to less developed countries [45] as well as technological progresses that have improved productivity through mechanization [11]. Ref. [46] underlined a stronger effect of mechanization when labour is scarce or expensive, while pesticides are used more intensively when land is expensive. On many occasions, chemical inputs were the solution to increasing productivity in order to face increasing labour costs [38], higher land prices, and growing competition [47–49].

Another set of complementary factors with potential impact on pesticide use are land fragmentation and farm size. When land is fragmented, it becomes more difficult to use farming equipment efficiently, which decreases productivity and increases costs [50]. The results of a survey of Chinese farmers point out that the use of pesticides does not necessarily depend on farm size but rather on certain psychological aspects: in order to preserve the soil, farmers use them less frequently when they believe the land to be clean, but more frequently when they believe their chances of remaining in agriculture are limited [51]. At the same time, recent research emphasizes the possibility of increased crop yields when using traditional farming methods. For example, crop rotation favours organic farming [52] and the participation of household labour in small farms improves farm efficiency [52]. Therefore, smaller traditional farms are more suitable for organic farming, while economies of scale can be obtained when farms are larger. Once the land is introduced into the organic farming circuit, producers cannot maintain certifications as organic farmers unless they change the type or amount of pesticides they use; this production system should maintain profitability over the long term [53]. The transition to organic farming imposes certain costs and changes in farm structure [54] that are not justified in the short term. In our analysis, we use the total organic agricultural area as a factor that is expected to negatively impact the use of pesticides. Many farms indicate a high level of farm fragmentation, so we initially tested the impact of the number of producers in agriculture (as a proxy for farm size) on the use of pesticides, but it turned out to be insignificant, as we eliminated the indicator from the final regression.

Regarding the drivers behind the transition to organic farming, it can be found that this depends on the possibility of making a profit coming from two main directions: higher selling prices and support payments for organic farming [55]. Normally, when product prices grow on the market, we would expect organic crop production to grow because, although the total costs in this segment are higher, farmers would have increased opportunities to make profit. However, more farmers are stimulated to meet market opportunities when they appear [56], and they continue producing even more inorganic products, which means a higher total pesticide usage. Other authors found that low-income farmers use more inorganic fertilizers, even in unnecessary amounts [57,58], while [59] identified a negative impact of farmer income on the efficiency of pesticide use. In our analysis, we test the impact of sales prices and real income on the consumption of pesticides.

Subsidies represent a solution for farmers to either: (1) invest in new technologies [60] that boost productivity as an alternative to the use of more chemicals or (2) sell organic farm products at competitive prices regardless of the technologies used [61,62]. However, the impact of subsidies on the consumption of pesticides should be interpreted according to the conditions applied by the states that offered subsidies in a given period of time. In the 1990s, eastern European countries withdrew many subsidies previously given to farmers to buy chemicals to improve agricultural productivity [63]. The policy's withdrawal in 2013, when the European Union introduced green payments (focusing on measures such as crop diversification) in the Common Agriculture Policy, led to a substantial decrease in yield [64]. Different types of pesticide subsidies have been applied in several European countries, including lower VAT rates (e.g., Austria, Belgium, Bulgaria, Croatia, France, Ireland, Italy, Poland, Portugal, Romania and Spain) [65]. However, some authors believe that that improved market access for organic products have greater overall effects than subsidies in reducing chemical use [66]. In other cases, the total value of available subsidies is not very relevant if the conditions imposed on farmers who access them are very restrictive or the contract terms are not flexible enough [67]. Taking these limits into account, in the current article, subsidies on agricultural products are expected to have a significant influence on pesticide consumption.

Specific social characteristics also determine the choice of certain types of farming method. For example, older, more experienced, and more educated farmers would be more prone to take the hard way and implement traditional methods [68]. The general education level of the population positively influences the demand for healthy food and therefore negatively influences the use of pesticides [66].

The main determinants of pesticide application identified in the literature were summarized in Table 1.

The intricacy of multiple problems that must be addressed simultaneously, as well as the link between different strategies, highlight the necessity for research that examines pesticide use in the context of the agricultural system and on a regional scale. Multicriteria evaluation and decision support systems, in conjunction with pest monitoring programmes, can aid in the development of region-specific and long-term policies that are coordinated within an EU framework.

### *2.2. Cluster Analysis of Pesticide Consumption in Agriculture*

A cluster analysis of agricultural systems provides categorization (and grouping) of countries, which can then serve as the basis for policymakers interested in establishing targets that clusters can strive to attain within certain time periods. This is of utmost importance since, on some occasions, management practices are not standardized, knowledge-sharing and learning from best practices are not well established, and systems frequently operate unaware and unconcerned about the performance of others around them.

**Table 1.** Selection of Primary Determinants in Pesticide Application.

| Determinants | | Implications | Correlation with Pesticide Use |
|---|---|---|---|
| Population increase (c) | | Food demand growth (a) [69] | Positive |
| Economic development (a) | low | Prohibitive pesticides costs (a) [40,41] | Positive |
| | high | Food demand growth = heavy users (a) [40,41] | Positive |
| | very high | Focus on efficiency and growing demand for healthy food (a) [40,41] | Negative |
| Scarce or expensive workforce (c) [46] | | Need to increase productivity (a) | Positive |
| Expensive land and growing competition (a) [47–49] | | | |
| Organic agricultural area | | Specific certifications for organic products (a) [53] | Negative |
| Sales prices of crop products increase (a) [56] | | Market for inorganic products becomes more profitable (a) | Positive |
| Real income increase (a) [57–59] | | Pressure to improve input efficiency decreases (a) | Positive |
| Subsidies increase (a) [60,64] | | Buy chemicals to improve agriculture productivity or<br>Possibilities to invest in sustainable farming methods (a) | Ambiguous |
| Farmer age and education increase (b) [68] | | Implementation of traditional farming methods (a) | Negative |
| Consumers' education increase (b) [66] | | Demand for healthy food (a) | Negative |

(a) economic factors, (b) social factors, (c) socio-demographic factors. Source: authors' computation based on literature review.

Cluster analysis have been used to identify patterns of energy and land use in agriculture [70], heavy metal sources in soils [71], and farmer search behaviour of various types of information, including pesticide use [72]. To our knowledge, cluster analysis has not been applied to the determinants of pesticide use in agriculture grouped at the geographical level.

## 3. Data and Methodology

### *3.1. Methods*

Given the ambitious goal of the European Union to reduce the use of chemical pesticides by 50% by 2030, the primary objective of this paper is to understand the influence of a set of economic and social variables on their use in the EU by conducting several regression analyses. We have considered the evolution of pesticide consumption between 2000–2019, and estimations were performed on panel data extracted from international databases [73,74] for all 27 member states (excluding the United Kingdom). The time frame is long enough to draw meaningful conclusions that are helpful in understanding the perspectives of the European Union in the field of agriculture.

Estimates were made using seemingly unrelated regressions, a method that takes into account heteroskedasticity and correlations between errors. The empirical study initially focuses on the influence of GDP per capita and selling prices of crop production on the use of pesticides. Given the complexity of the topic and the variety of factors that influence the use of pesticides, we have expanded our model with other variables referring to the governmental support granted to agriculture and (subsidies on agricultural crops) and a social-demographic variable (population in each member state) (Equation (2)). Furthermore, given the EU's ambitious goal of improving the health of its citizens, we subsequently included an independent variable related to the organic crop area in Equation (3). Lastly, the FAO-calculated index of real income factors in agriculture was added as an explanatory variable to account for the impact of factor productivity on pesticide use [75]. Initially, we have estimated the regression by including independent variables: employment in agriculture (1000 persons), labour force participation rate in rural areas (% of total population ages 15+), number of producers in agriculture, export value index for agricultural products (2014–2016 = 100) and number of people who completed tertiary education. However, these variables had no significant impact in the regression and were not preserved in the estimations presented below, representing one of the limits of the research. With the purpose of examining the determinants of the use of chemical pesticides in the EU (27) between 2000 and 2019, we have estimated an empirical model based on panel data, gradually extending the equations with explanatory variables, specifically related to the agricultural sector or aiming at the macroeconomic and social framework, as follows:

$$Pesticides_{i,t} = a + \beta_1(GDP\ per\ capita_{i,t}) + \beta_2(Selling\ prices_{i,t}) + u_{i,t} \quad (1)$$

$$Pesticides_{i,t} = a + \beta_1(GDP\ per\ capita_{i,t}) + \beta_2(Selling\ prices_{i,t}) + \beta_3(Subsidies_{i,t}) + \beta_4(Population_{i,t}) + u_{i,t} \quad (2)$$

$$\begin{aligned} Pesticides_{i,t} = \; & a + \beta_1(GDP\ per\ capita_{i,t}) \\ & + \beta_2(Selling\ prices_{i,t}) + \beta_3(Subsidies_{i,t}) + \beta_4(Population_{i,t}) + \beta_5(Organic_{i,t}) + u_{i,t} \end{aligned} \quad (3)$$

$$\begin{aligned} Pesticides_{i,t} = \; & a + \beta_1(GDP\ per\ capita_{i,t}) \\ & + \beta_2(Selling\ prices_{i,t}) + \beta_3(Subsidies_{i,t}) + \beta_4(Population_{i,t}) \\ & + \beta_5(Organic_{i,t}) + \beta_6(Real\ income_{i,t}) + u_{i,t} \end{aligned} \quad (4)$$

where $a$ = constant, $u_{i,t}$ = error term; $t$ = 1, ..., T (years); $i$ = 1, ..., N (countries)

The variables, definitions, sources, and the expected influence are presented in Table 2.

**Table 2.** Variables, definitions, and sources used in the first empirical model.

| Variable | Definition | Source |
|---|---|---|
| Pesticides | Pesticide use per area of cropland (kilograms per hectare) | Our World in Data |
| GDP per capita | Real GDP per capita (chain-linked volumes 2010, euro per capita) | Eurostat |
| Selling prices | Sales prices of crop products (absolute prices, euro per 100 kg) | Eurostat |
| Subsidies | Subsidies on agricultural products (million euro) | Eurostat |
| Population | Population (total number) | Eurostat |
| Organic agricultural area | Hectares of organic crop area fully converted and under conversion to organic farming) | Eurostat |
| Real income | Index of the real income of factors in agriculture per annual work unit (2010 = 100) | Eurostat |

Source: Authorial computation.

Panel data for all variables were tested for stationarity by using the Levin, Lin & Chu unit root test [76]. By applying this test, we have started from the hypothesis that the data have a unit root and are not stationary. Initially, we tested for stationarity using an individual intercept and trend, then with an individual intercept or no regressors. If the data did not show stationarity at level, we have checked for the first difference. The data were tested at level, initially including the trend and intercept in the equations. If using this variant revealed that the panel data have a unit root, we resorted to including only intercept or no regressor in the equation. Given the results obtained by applying the root tests (Prob. < 5%), we concluded that the data is stationary at level for all variables, except for the organic agricultural area (Table 3).

**Table 3.** Stationarity test.

| Panel Unit Root Test-Levin, Lin & Chu [76] | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Type of Test** | **t-Statistic** | **Prob.** | **Cross-Sections** | **Obs.** |
| Pesticides' use | level, individual intercept and trend | −5.24169 | 0.0000 | 26 | 494 |
| GDP per capita | level, individual intercept and trend | −1.75557 | 0.0396 | 27 | 484 |
| Selling prices | level, individual intercept and trend | −10.3856 | 0.0000 | 25 | 426 |
| Subsidies | level, individual intercept and trend | −3.34717 | 0.0004 | 26 | 378 |
| Population | level, individual intercept and trend | −5.43467 | 0.0000 | 27 | 486 |
| Organic agricultural area | level, individual intercept and trend | −0.00809 | 0.4968 | 27 | 427 |
| | level, individual intercept | 1.49809 | 0.9329 | 27 | 427 |
| | level, none | 1.49809 | 0.9329 | 27 | 427 |
| | 1st difference, individual intercept and trend | −7.28873 | 0.0000 | 27 | 400 |
| Real income | level, individual intercept and trend | −4.1117 | 0.0000 | 27 | 455 |

Source: Authorial computation.

### *3.2. Cluster Analysis*

A cluster analysis was carried out based on the most relevant factors in the use of inorganic pesticides that had a significant influence in the regressions ($p$-value less than 10%). The analysed variables were the following: GDP per capita, population, sales prices, subsidies, organic agricultural area, index of real income of factors in agriculture, all having equal weight in the cluster formation. Cluster analysis is applied at a one-year level. The most recent year for which statistics were available was chosen (2019 in most cases, except France, where the last available data for selling prices are from 2016). Cyprus and Malta were excluded from the cluster analysis due to the lack of data on sale prices.

Since the variables were different sizes and to prevent large-scale variables from dominating the cluster formation, the data have first been normalized to have a mean of 0 and a variation of 1. We have used SAS software and applied the Ward minimum variance method, which groups observations based on the minimum distance between them (the distance being the ANOVA sum of squares). Clusters are grouped in subsequent stages at each level of the hierarchy until we obtain the optimum number of clusters, which have the maximum distance between them [77].

## 4. Results and Discussion

### *4.1. Regression Analysis*

Table 4 illustrates the statistical description of the variables included in the empirical model. At first glance, the differences between the minimum and maximum values emphasize the heterogeneous evolution among the member states in the field of macroeconomic, social, and agricultural related variables. The average amount of pesticides used per hectare in the European Union was 3.1 kg, with significant differences between member states. For example, countries such as the Netherlands and Belgium had a consumption of pesticides greater than 12 kg per hectare, while the Baltic States and Bulgaria recorded values under half kilogram per hectare. In the field of economic development, the GDP per capita suggests a heterogeneous evolution among member states, with an average income of 24,279 euros for the time interval 2000–2019. In terms of agricultural sector performance, the average selling prices for agricultural products were 15 euros per 100 kg, with Italy and France recording the highest performances. Referring to the amount of subsidies granted to agriculture, the average value recorded between 2000 and 2019 was 331 million euros, with significant differences between member states. The highest amounts were given to France (5121 million euros) and Germany (3335 million euros), while the countries that benefited the least from the subsidies were Slovakia, Denmark, and Ireland. For the entire period, the average surface aimed at organic agriculture was 337,059 hectares per member state, while in the field of real income in agriculture, the mean value of the index was 102.48 euros.

**Table 4.** Statistical description of the variables in the empirical model.

| Variable/ Indicator | Mean | Median | Max. | Min. | Std. Dev. | Obs. |
|---|---|---|---|---|---|---|
| Pesticides | 3.153327 | 2.260000 | 12.06000 | 0.240000 | 2.720559 | 520 |
| GDP per capita | 24,279.59 | 20,245.00 | 88,120.00 | 2990.000 | 16,500.82 | 538 |
| Selling prices | 15.05340 | 14.97000 | 33.07000 | 7.940000 | 3.881449 | 476 |
| Subsidies | 331.1159 | 34.52000 | 5121.500 | 0.010000 | 816.3447 | 439 |
| Population | 16,239,962 | 8,343,323 | 83,019,213 | 388,759.0 | 21,354,486 | 540 |
| Organic agricultural area | 337,059.8 | 167,538.0 | 2,354,916 | 1.000000 | 440,774.1 | 482 |
| Real income | 102.4768 | 100.0000 | 250.3800 | 33.60000 | 29.49577 | 509 |

Source: Authorial computation.

Given the estimated values of the coefficients presented in Table 5, the equations are as follows:

$$\begin{aligned} Pesticides_{i,t} = \; & -5.6136 + 0.2252(GDP\ per\ capita_{i,t}) \\ & +0.5727(Selling\ prices_{i,t}) + u_{i,t} \end{aligned} \quad (5)$$

$$\begin{aligned} Pesticides_{i,t} = \; & -8.9782 + 0.5787(GDP\ per\ capita_{i,t}) \\ & +0.1098(Selling\ prices_{i,t}) - 0.0024(Subsidies_{i,t}) + 0.2312(Population_{i,t}) + u_{i,t} \end{aligned} \quad (6)$$

$$\begin{aligned} Pesticides_{i,t} = \; & -9.4161 + 0.5466(GDP\ per\ capita_{i,t}) \\ & +0.2299(Selling\ prices_{i,t}) - 0.01224(Subsidies_{i,t}) + 0.4083(Population_{i,t}) \\ & -0.1948(Organic_{i,t}) + u_{i,t} \end{aligned} \quad (7)$$

$$\begin{aligned} Pesticides_{i,t} = \; & -10.8320 + 0.5097(GDP\ per\ capita_{i,t}) \\ & +0.0829(Selling\ prices_{i,t}) - 0.0067(Subsidies_{i,t}) + 0.4327(Population_{i,t}) \\ & -0.1902(Organic_{i,t}) + 0.3710(Real\ income_{i,t}) + u_{i,t} \end{aligned} \quad (8)$$

Table 5 and the estimation presented above illustrate the results of the empirical analysis aimed at identifying pesticide determinants of use in the European Union. Pesticide use was mainly influenced by the economic performance of the member states, particularly the level of GDP per capita. Consequently, an increase of one euro of GDP per capita will determine a rise of 0.5 kg of pesticide use per hectare, according to Equation (4). The increase in GDP per capita had a positive and strong influence on the use of pesticides in the European Union, confirming that many developed countries are still heavy users of pesticides. Our results are in line with [78], which also showed a positive connection between pesticide consumption, population and GDP per capita for several countries, including Europe, between 1990 and 2014. We cannot firmly contradict [40,41] which showed an inverted U-shaped evolution of pesticides along with GDP growth because we only checked a linear relationship applying a regression model for the entire time frame. Looking at the primary data that we used in the sample, one can find that several countries have reduced pesticide consumption over recent years (from 2017, 2018, or 2019) after increasing it between 2010 and 2016: Austria, Belgium, Bulgaria, Czech Republic, France, Germany, Italy, Netherlands, Poland, Portugal, and Sweden. Other countries have continued to use more pesticides until 2019: Croatia, Estonia, Latvia, Romania, Slovakia, and Spain. Although GDP per capita has continuously grown in the mentioned countries from 2010 to 2019, we can only associate a decrease in pesticide use with a higher GDP per capita for two or three years. This trend should be followed for a few more years to be able to draw more pertinent conclusions.

**Table 5.** Regression output.

| Dependent Variable: Annual Pesticides' Use (2001–2019) | | | | |
|---|---|---|---|---|
| **Method: Generalized Least Squares-Seemingly Unrelated Regression** | | | | |
| **Equation** | **1** | **2** | **3** | **4** |
| **No. Obs./ Variable** | **474** | **408** | **375** | **361** |
| C | −5.6136 * (0.3812) (−14.7237) | −8.9782 * (0.5365) (−16.7321) | −9.4161 * (0.5459) (−17.248) | −10.8320 * (0.5862) (−18.477) |
| GDP per capita | 0.2252 * (0.2148) (1.0485) | 0.5787 * (0.0409) (14.1375) | 0.5466 * (0.0495) (11.0409) | 0.5097 * (0.0463) (10.9983) |
| Selling prices | 0.5727 * (0.0377) (15.1749) | 0.1098 * (0.0303) (3.6202) | 0.2299 * (0.0412) (5.5710) | 0.0829 *** (0.0441) (1.8799) |
| Subsidies | | −0.0024 (0.0049) (−0.4892) | −0.0122 ** (0.0054) (−2.2562) | −0.0067 (0.0055) (−1.2197) |
| Population | | 0.2312 * (0.0227) (10.1592) | 0.4083 * (0.0306) (13.3363) | 0.4327 * (0.0306) (14.1349) |
| Organic agricultural area | | | −0.1948 * (0.0232) (−8.3907) | −0.1902 * (0.0242) (−7.8432) |
| Real income | | | | 0.3710 * (0.0507) (7.3132) |
| Prob (F-statistic) | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $R^2$ | 0.3441 | 0.3316 | 0.4005 | 0.4508 |
| Adjusted $R^2$ | 0.3413 | 0.3250 | 0.3924 | 0.4415 |
| Durbin–Watson stat | 1.9784 | 1.9254 | 1.8424 | 1.7928 |

Note: robust standard errors and t-statistics are in parentheses. *—*p*-value < 1%, **—*p*-value < 5%, ***—*p*-value < 10%. Source: Authorial computation.

The analysis shows that farmers tend to use more chemical pesticides as the population of EU member states increases, indicating a potential increase in food demand. The population growth of one unit generates a 0.43 kg per hectare increase in pesticides (Equation (4)). This finding confirms the relationship between the increase in demand and the response to improve productivity (in line with [69]). Consequently, European farmers still place a priority on producing a large amount of food, while the production of healthy, high-quality food (including few or no pesticides) is less attractive. The increase in demand (expressed as a higher quantity) is still a more interesting opportunity compared to the advantages of organic agricultural production. The profits obtained from organic farming may not yet be enough to determine the specialization in this area. For example, ref. [79] found a similar profit per surface of cultivated land for conventional and organic farming in certain regions in Germany.

Another factor that had a high influence on the dependent variable was real income, which determined an increase in pesticide use of 0.37 kg per hectare (Equation (4)). Moreover, having a high statistical significance in Equation (1), the resulting coefficients suggest that an increase with 1 euro of selling prices per 100 kg determines a rise in the quantity of pesticide per hectare of 0.57 kg. Therefore, when profits are higher, producers prefer to retain them rather than invest in the switch to organic farming, confirming that the behaviour observed by [56], as presented in the literature review, continues to manifest in the same way. When income increases, the preoccupation with efficiency diminishes and more pesticides are wasted, similar to what [59] found in Chinese agricultural practices.

Although not statistically significant in the second and fourth equations, subsidies granted to agricultural products tend to negatively influence the consumption of pesticides. Their growth in one unit leads to a decrease in pesticide consumption of 0.0067 kg per hectare. This result is probably due to the orientation of these funds toward organic farming. This is an interesting finding because it confirms the fact that if a certain conditionality is imposed on accessing subsidies, such as following sustainable farming methods, it would motivate farmers to embrace them and still have sufficient profit. Ref. [80] also identified direct subsidies to be effective in determining a switch to organic farming practice, but that it also caused a price decrease for both organic and conventional farming output. The decrease in the output price for organic products makes them more available to consumers, but when prices for conventional farming products are also lower, the profits for this specialization also decrease. This is when subsidies directed to organic farming compensate for the profit loss. Ref. [55] pointed out that both increased prices and subsidies for organic farming are effective methods to increase profits and encourage farmers use sustainable production methods.

The results also suggest that the increase in the area intended for organic agriculture tends to negatively influence the consumption of chemical pesticides, as the independent variable is significant in the estimations. More specifically, the expansion with one hectare of organic farming creates a decrease in pesticide use of 0.19 kg per hectare (Equation (4)). This relationship is obvious because organic farming means using fewer synthetic pesticides [81]. The question that needs to be further explored is whether an increase in the surfaces dedicated to organic agriculture determines a progressively higher reduction of chemical pesticide use as more farmers learn from the experience and as certain economies of scale or scope can be obtained. However, such an analysis can only be performed when and where sustainable agriculture is more widely spread.

The values of the coefficient of determination (R2) imply that the model explains the variation of the dependent variable in a percentage that spans from 34% (Equation (1)) to 45% (Equation (4)). To check the validity of the model, we tested the classical linear regression assumptions. The general form of the multiple linear regression is as follows:

$$Y_{i,t} = a + \beta X_{i,t} + u_{i,t}$$

where $Y_i$ = dependent variable; $X_{i,t}$ = independent variable; $u_{i,t}$ = error term $t$ = 1, . . . , T (time); $i$ = 1, . . . , N (cross-sections).

First, we have verified whether there is serial independence, which assumes that the errors are distributed independently. To test the first-order correlation, we used the Durbin–Watson test. The value of around 2 confirms that there is no first-order correlation between errors, so we consider that the empirical model is valid. Subsequently, we have tested the validity of the model by looking at another assumption of the linear regression model, the multicollinearity, which implies that the explanatory variables are not correlated. To identify multicollinearity, we used the VIF test (variance inflation factors). As described in Table 6, the results of the centred VIF are around 1 for all variables. Consequently, we have concluded that there is not a highly collinear relationship between explanatory variables that could bias the estimates. We have also tested another assumption of the linear regression model—the homoscedasticity—which assumes that all error terms have the same variance, respectively $var(\varepsilon_{i,t}) = \sigma^2$ = constant for all $t$ [73]. The histogram confirms that the residuals have a normal distribution, with a probability value above 5%. Finally, we have tested whether the explanatory variables are representative. The redundant variable test illustrates that the variable related to the population is significant, as we have rejected the null hypothesis. Moreover, we were also interested in determining if another variable initially taken into consideration for the estimation was omitted in the model. By accepting the null hypothesis (Prob. > 5%), we concluded that agriculture (% of GDP) would not be significant (Table 7).

**Table 6.** Variance Inflation Factors.

| Variance Inflation Factors | |
|---|---|
| **Variable** | **Centred VIF** |
| GDP per capita | 1.1476 |
| Selling prices | 1.1878 |
| Subsidies | 1.2151 |
| Population | 1.9623 |
| Organic agricultural area | 1.7374 |
| Real income | 1.2083 |

Source: Authorial computation.

**Table 7.** Coefficient diagnosis.

| **Test** | **Null Hypothesis** | **Result** | | | | **Decision** |
|---|---|---|---|---|---|---|
| Redundant variable test | Population is not significant | | Value | Df | Probability | Reject the null hypothesis |
| | | t-statistic | 11.3756 | 354 | 0.0000 | |
| | | F-statistic | 129.4044 | (1, 354) | 0.0000 | |
| Omitted variable test | Agriculture (% of GDP) is not significant | | Value | Df | Probability | Accept the null hypothesis |
| | | t-statistic | 1.6448 | 353 | 0.1010 | |
| | | F-statistic | 2.7043 | (1, 353) | 0.1010 | |

Source: Authorial computation.

### *4.2. Cluster Analysis*

The next step involved clustering the European countries based on the factors of pesticide consumption that we found in the regression models. The goal was to identify similar arrangements of these drivers so that comparable pesticide mitigation strategies could be developed. Based on the Ward method's application of the following criteria, we have obtained three clusters, as shown in Table 8. Pseudo F statistic (14.6) and cubic cluster criterion (0.28) were high showing a high separation between clusters, while pseudo T-squared was low (5.4) indicating that the variance between clusters relative to the variance within clusters is low. Figure 1 illustrates the cluster formation stages. The red line marks the stage in which the three clusters were obtained.

**Table 8.** The groups obtained in the cluster analysis.

| **Cluster Number** | **Countries within Each Cluster** |
|---|---|
| 1 | Italy, Spain, France, Germany |
| 2 | Poland, Lithuania, Greece, Portugal, Slovenia, Estonia, Romania, Croatia, Latvia, Czech Republic, Hungary, Slovakia, Bulgaria |
| 3 | Ireland, Luxembourg, Finland, Denmark, Netherlands, Belgium, Sweden, Austria |

Source: Authorial computation.

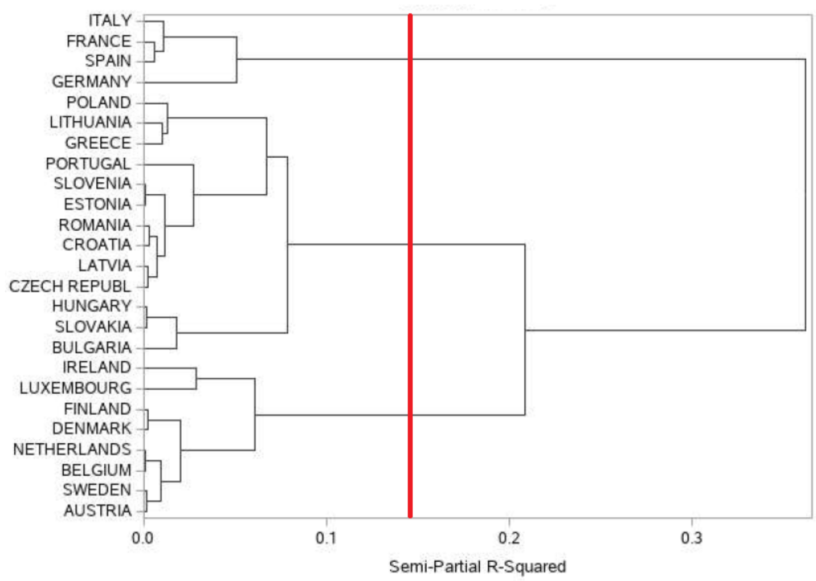


**Figure 1.** Hierarchical clustering tree. Source: Authorial computation.

Based on the average values that the variables take in each country (Table 9), we further comment on the main characteristics and propose a set of recommendations in each case.

**Table 9.** Average values of variables in each cluster.

| Cluster no. | GDP per Capita | Population | Selling Prices | Subsidies | Real Income | Organic Crop Area |
|---|---|---|---|---|---|---|
| 1 | 30,427.50 | 64,237,645.50 | 18.85 | 253.20 | 125.62 | 1,969,944.25 |
| 2 | 14,486.92 | 9,496,740.62 | 16.58 | 94.26 | 151.16 | 291,458.85 |
| 3 | 48,998.75 | 8,083,597.00 | 15.38 | 3.79 | 104.87 | 265,543.88 |

Source: Authorial computation.

The first cluster is the most homogeneous (semi-partial R-squared is 0.0506) and contains three of the founding member states (Italy, Germany, and France) together with Spain, which joined the EU in 1986. These are the countries with the largest population in our sample (64 million people on average) and the largest organic crop area (1.97 million hectares on average), which is not surprising given the large territory of these countries. The total subsidies for agriculture are the highest in this cluster (an average of 253.2 million euros), especially in the case of France (306.16 million euros) and Spain (301.93 million euros), although this does not translate into lower selling prices for agricultural products. Compared to other clusters, this one exhibits the largest average value for selling prices (18.85 euros per 100 kg). However, since subsidies are expressed in absolute terms and are not related to either the quantity of products or the cultivated surface, we cannot establish a clear connection between subsidies and sales prices. The average GDP per capita (30,427.50 euros) and the average real income of the factors in agriculture are at middle levels among the three clusters, indicating good possibilities to develop organic agriculture, but also putting the producers in a more comfortable situation, which brings little motivation to switch to sustainable agriculture.

Most of the newest EU members (Poland, Lithuania, Slovenia, Estonia, Latvia, Czech Republic, Hungary, Slovakia, Romania, Bulgaria, and Croatia) and two South European countries (Greece and Portugal) are included in the second cluster, which has the highest disparities, as suggested by the highest semipartial R-squared in the dendrogram (0.05060). This cluster has the smallest average GDP per capita (14,486.92 euros). Their population (9.5 million people on average) and organic crop farming area (291,459 hectares on average) are between the other clusters, but closer to the average figures in the third cluster. The level of subsidies is larger than in the third cluster (94.26 million euros on average). The average of the index of real income of factors in agriculture per annual work unit is the highest for this cluster, showing that farmers obtain high productivity and good development possibilities in agriculture. Although these countries lag in terms of economic development, which could indicate a lower demand for organic food, they could serve other developed markets through the single market as well.

The third group consists of Northern and Western European countries and, among the three clusters, it occupies a middle position in terms of homogeneity (semipartial R-squared equals 0.06094). Its members (Ireland, Luxembourg, Finland, Denmark, Netherlands, Belgium, Sweden, Austria) are characterized by having the highest GDP per capita (48,998.75 euros on average), a smaller population compared to the other clusters (8 million people on average), the lowest level of subsidies for agriculture (3.79 million euros on average), and the lowest real income in agriculture (an average index of 104.87). This occurs against a backdrop of limited agricultural specialization, which is specific to developed countries with small surfaces, low population, or scarce population in general. However, existing agricultural production, even if smaller, has the prerequisites to be turned into organic agriculture, improving the quality of the products, and addressing high income markets. Indeed, the average organic crop area (265,544 hectares) is close to the one reported by the countries in the second cluster. Austria (671,703 hectares) and Sweden (613,964 hectares) even have a higher organic crop area than any country in the second cluster. The selling prices of farm products are the smallest in the case of this cluster (an average value of 15.38 euros per 100 kg), and when combined with the small level of subsidies for agriculture and small real income, they indicate a lower profitability of agriculture currently. Although prices are low, an increase in direct subsidies might be possible to counteract this disadvantage for producers.

## 5. Conclusions and Recommendations

This paper consists of an analysis built up in two main stages. The first carried out a set of four seemingly unrelated regressions aimed at identifying the impact of various economic and social determinants on the consumption of pesticides in EU member countries, and the second retained the determinants with a significant impact to be used as factors in the cluster analysis. It resulted in three main clusters that place the member countries on different levels of similar conditions that determine the current level of pesticide consumption and represent barriers or opportunities to switch to sustainable agricultural practices.

Our study revealed that wealthy countries use more pesticides in agriculture, but on a downward trend over the previous two or three years, as wealthier consumers can afford healthier food. GDP per capita had the greatest impact on pesticide use (a 0.50 coefficient in the fourth equation). A larger population determines the use of more pesticides (coefficient: 0.43), establishing the link between food demand and productivity pressure.

From the supply perspective, results showed a positive and asymmetrical influence of sale prices of agricultural products ($p$-value < 10%) and real income of agricultural components ($p$-value less than 1%) on the inputs of pesticides. This emphasises the fact that improved market opportunities, expressed through favourable prices, motivate farmers to produce more, sell more and gain more profit.

As organic crop area grows, pesticide input decreases, showing that organic farming experience encourages sustainable pest control. Although conventional agriculture is still profitable, subsidies, especially those targeted at sustainable production techniques, are the only economic leverage that can push farmers to investigate alternative pest management methods and reduce synthetic pesticide use.

The cluster analysis resulted in three country clusters on which we can draw the following conclusions and recommendations.

- Research and development and sharing expertise with other market participants might improve the experience of having a large organic agricultural area for the nations with the biggest population and GDP per capita (Italy, Spain, France, Germany).

This cluster's subsidies are higher than others, but better targeting, complementary regulatory circumstances, market access, etc. can increase their efficiency.
- The second cluster (Poland, Lithuania, Greece, Portugal, Slovenia, Estonia, Romania, Croatia, Latvia, Czech Republic, Hungary, Slovakia, Bulgaria) has average pesticide use determinants. Competitive prices and large agricultural surfaces could benefit these countries. Subsidies can be increased while imposing their use in sustainable farming procedures, and there is a great deal of work to be completed in terms of regulations, market access for organic products not only on their own markets, but also on other European markets where consumers have higher incomes to spare on healthy food.
- Ireland, Luxembourg, Finland, Denmark, Netherlands, Belgium, Sweden, Austria, and Luxembourg had the lowest agricultural production and subsidies in the third cluster. More in-depth studies are needed to see for which type of crop, subsidies would not represent a waste of resources given the more difficult environmental conditions.

Originality elements for this study derive from the complementary study of determinants of pesticide consumption that considers the synergies between the agricultural, macroeconomic, and social levels, and the analysis of regional differences reflected in the cluster analysis. Consequently, our findings can contribute to the creation of targeted national sustainable production policies and the design of practical measures by providing specific quantitative information.

The analysis takes into consideration crop production as a whole without being able to differentiate between organic and conventional farming. Such a distinction would have been useful for variables such as sales prices, real income, and subsidies. In the case of some explanatory variables (subsidies on agricultural products), data for some member states were not available for the entire period of time. However, we were aware of this down side at the beginning of this study and believed that the estimation would not be biased.

Given the impossibility of capturing the multitude of factors that influence pesticide consumption, another limit of the study derives from the restrained set of parameters included in the empirical models. Future research can address the study of other social, economic and technical factors specific to the farm environment that affect the acceptance of sustainable production methods, continuing a previous work on good practices for lowering the use of pesticides and fertilizers [82].

Another important research direction would be to deepen the examination of the conditions under which subsidies or other forms of public financial support would be efficient in extending sustainable agriculture practices. Diversified farming systems that combine conventional and sustainable agriculture production methods are perhaps worth considering; this was also identified as a research direction in [83].

Eliminating pesticide use is difficult. Farmers have few pest and weed control choices after years of relying on them. Many farmers, especially those who have invested in conventional farms, cannot afford alternative pest treatment equipment and longer production time. However, a rise in organic farms, knowledge of sustainability in modern agriculture, and government-sponsored efforts are propelling the biopesticide business and pushing more farmers to adopt sustainable agricultural production.

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