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CIRCULAR AGRONOMICS

D4.1. Barriers to acceptance for the adoption of new farming practices

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### **1. Overview: Farmer adoption of sustainable farming practices and the development of a farm survey**

A systemic review of factors and conditions that affect adoption of sustainable technologies and practices by farmers in the European Union was completed and published in Sustainability in December 2020. Specifically, it reviews recent empirical studies regarding adoption of organic farming, manure treatment and manure-based fertilization, and various soil and water conservation measures. While being technologically separate and independent, they all contribute to a reduction in nutrient surplus, which is a serious soil quality problem threatening sustainable food production. All of the reviewed technologies are important elements of the circular economy that stands on the principles of recyclability of resources and minimization of waste. This is the first published review to combine all the three types of farm management practices under one theoretical umbrella, using mainstream social psychology approaches such as the theory of planned behaviour. The outcomes of this review are of particular relevance to European policymakers in the formulation of policies that are evidence based and targeted for the conservation, preservation, and sustainable management of natural resources in agriculture.

In addition, a farm survey across the case study regions of the Circular Agronomics project has been undertaken by CREDA in conjunction with TEAGASC. A survey instrument was designed using a range of approaches approaches to measure risk, attitudes, opinions, and preferences, as well as the willingness to accept new technologies (WTA) by farmers. The questions were presented in blocks according to the type of information such as: structure of the farm, the socioeconomic characteristics of the farmers, risk' opinions and perceptions, environmental attitudes, farmers' preferences on sustainable agricultural activities and the adoption on farm innovations. All items were selected based on the extensive literature review of the factors that influence the acceptance of and decision to adopt sustainable innovations by farmers.

The pilot survey, with first version presented in Catalan (M17-18), and was subsequently modified to address the comments and suggestions of the farmers interviewed within the test phase in the region of Catalonia. The english version was subsequently generated and shared with the partners and case study leaders. Based on their feedback, the survey questions were updated and grouped into the general part, presented to all farmers, and the technology-specific parts, each containing questions about innovations proposed to farmers in different case study countries. In Spain, within the region of Catalonia, the innovations were "precision feeding system" and "treatment of manure/slurry through a thermal/solar dryer". In Italy, in the region of Emilia Romagna, the new technology was "Fertigation with microfiltered slurry/digestate". The innovation presented in Lungau, Austria

corresponds to "Low-input farming" and in the Czech Republic in South Moravia the innovation that was proposed was on the use of "Nanofiber membranes".

Subsequently, with the help of the case study leaders, the translation of their respective surveys into the local languages (Spanish, German, Italian, Czech, and Dutch) was carried out and the final online version for each country was generated, available through the Qualtrics platform. This link was then shared by case study leaders with farmers in their countries and a close and continuous follow-up of the progress of the applied surveys was maintained with them. In total, 149 farmer responses were collected which included 51 in Spain, 57 in Italy, 34 in Austria, 1 in the Netherlands, and 6 in the Czech Republic.

## **2. Findings: Summary of literature review and the preliminary survey results**

The aim of the literature review was to explore factors and conditions affecting EU farmers' adoption of nutrient reduction strategies. The specific focus was on widely adopted and empirically explored measures, such as organic farming, manure treatment technologies and manure fertilization, as well as soil and water conservation methods. In total, 23 peer-reviewed studies were extracted by the means of Google scholar covering the time period between 2003 and 2019 as detailed in Table 1. The main findings show that farmers' environmental and economic attitudes in addition to their sources of information have a strong effect on adoption of organic farming, although there is lack of evidence of their impact on adopting manure treatment and conservation measures. Similarly, farmers' age and education are found to systemically influence organic farming adoption, but not adoption of other reviewed technologies. While other factors, such as farm physical characteristics or technological attributes, may be important determinants of adoption, it is hard to recognize definite patterns of their impact across technologies given a shortage of empirical evidence. More research utilizing standardized surveys and methods of analysis is needed to formulate qualified guidelines and recommendations for policy makers.

In addition to the review for this deliverable, previous reviews of adoption studies focused primarily on conservation technologies. For example, Knowler and Bradshaw (2007) reviewed adoption studies of conservation tillage, crop rotation and cover crops in developing countries and North America, summarizing both the direction and significance of statistical effects of adoption factors. In a similar paper, Wauters and Mathijs (2014) performed a meta-analytic review of factors affecting the adoption of conservation measures in the U.S., Canada and Australia. Furthermore, Carlisle (2016) narratively reviewed determinants of adoption of various soil health practices in application to agricultural commodity production in the U.S. Our review extends these papers by focusing on recent adoption studies of soil and water conservation in focusing solely on research from Europe, while also complementing them with a review of factors affecting adoption of organic farming and manure treatment technologies. To the best of our knowledge, there are just a few examples of literature reviewing factors of adoption of sustainable farming in Europe. For example, Lahmar et al. (2010) provided a general (non-critical) overview of drivers and constraints of conservation agriculture development in such countries as Italy, Spain, France and Czech Republic. Separately, Prager and Posthumus (2010) reviewed determinants of adoption of soil conservation measures in several EU countries, using responses to standardized farmer surveys. Liu et al. (2018) also mentioned several European studies in their review of factors of farmers' adoption of best management practices aimed at the reduction in non-point source pollution. More recently, Dessart et al. (2019) provided a policy-oriented review of behavioral factors influencing the adoption of various sustainable farming practices in Europe, such as organic farming and conservation agriculture. While this paper covers several studies also mentioned in our review, it focuses exclusively on behavioral factors of adoption such as farmer attitudes while

disregarding other common determinants of adoption (e.g., farmer demographic attributes). Additionally, it covers studies on adoption of agri-environmental schemes, which is beyond the scope of the given review.

For more details concerning the technology adoption review, please see the full version of the peer-review paper by following the link below: Serebrennikov, D.; Thorne, F.; Kallas, Z.; McCarthy, S.N. Factors Influencing Adoption of Sustainable Farming Practices in Europe: A Systemic Review of Empirical Literature. Sustainability 2020, 12, 9719. <https://doi.org/10.3390/su12229719>

**Table 1.** Summary of empirical studies on adoption of sustainable farming practices in the EU

Author(s) & year	Area <sup>3</sup>	Technology/ Measure	Sample size	Model	Farm type
<b>Organic farming</b>					
Läpple & Van Rensburg (2011)	IE	Organic farming	546	Multinom logit	Various types (drystock)
Genius et al (2006)	EL	Organic farming	237	Ordered probit	Multi-crop
Mzoughi (2011)	FRA	Organic farming	243	Multinom logit	Fruit & vegetables
Kallas et al.(2010)	ES	Organic farming	120	Duration analysis	Vineyard
Burton et al. (2003)	UK	Organic horticulture	237	Duration analysis	Horticulture
Chatzimichael et al. (2014)	EL & DE	Organic farming	282	Probit	Horticulture, crops
Läpple & Kelley (2015)	IE	Organic farming	597	Bayesian probit	Various types (drystock)
Koesling et al. (2008)	Norway	Organic farming	1018	Multinomial logit	Dairy and crop
Tiffin and Balcombe (2011)	UK	Organic farming	237	Bayesian probit	Horticulture
Läpple & Kelley (2013)	IE	Organic farming	193	Probit	Drystock
Kaufmann et al. (2009)	EE & LV	Organic farming	4917	Agent-based modelling	Various
<b>Manure treatment and manure-based fertilizers</b>					
Gebrezgabher et al. (2015)	NL	Manure separation	111	SUR/Ordered probit	Dairy
Zemo and Termansen (2018)	DK	Collective biogas investment	461	Mixed logit	Cattle and pigs
Pampuro et al. (2018)	IT	Pelletized compost	82	No model	Various non-livestock
Hou et al. (2016)	EU <sup>1</sup>	Manure treatment	96	No model	Pigs, poultry, cattle
Rentala et al. (2017)	FI	Technological, service & business model	139	Linear regression	Horse farms
Case et al. (2017)	DK	Organic fertilizers	452	Probit	Arable, horticulture, & livestock
Tur-Cardona et al. (2018)	EU <sup>2</sup>	Bio-based fertilizers	555	Random parameter logit / Latent class	Crop, livestock, horticulture
<b>Soil &amp; water conservation</b>					
Buckley et al. (2012)	IE	Riparian buffer zone	247	Gen tobit/Probit	Dairy, arable, livestock
Giovanopoulou et al. (2011)	EL	Nitrogen reduction	125	Probit/OLS	Not specified
Gachango et al. (2015)	DK	Water conservation	267	Ordered probit	Crop, cattle & pigs

Rodriguez-Entrena & Arriaza (2013)	ES	Soil conservation	232	Multivar probit	Olive growers
Carmona et al. (2015)	ES	Soil conservation	30	No model	Wheat and sunflower

**Notes:**

<sup>1</sup>This study covered Denmark, Italy, Netherlands, and Spain.

<sup>2</sup>This study covered Belgium, Denmark, France, Netherlands, Germany, and Hungary.

<sup>3</sup>Country abbreviations: IE – Ireland, EL – Greece, FRA – France, ES – Spain, UK – United Kingdom, DE – Germany, EE – Estonia, LV – Latvia, NL – Netherlands, DK – Denmark, IT – Italy, FI – Finland.

**Farmer Survey Results**

CREDA is currently leading the analysis of the farmer data collected in conjunction with TEAGASC, which will enable the identification of the main factors or characteristics that affect the decision to adopt the proposed agricultural innovations. A brief overview of the analysis to date is presented in Tables 2 – 4 below with a more detailed comparison of characteristics of technology adoption in Table 5. In summary, tables 2 to 4 show that farmers are primarily male, manage their own farm and have the previous technology-adoption experience. However, their adoption plans are primarily driven by economic rather than social or ecological objectives. Nearly half of all farmers in the survey indicated their willingness to adopt new technological innovations, with over two thirds claiming that it would be very interesting to do. These initial findings show a clear role for promoting some of the circular agronomic practices developed in the case study regions.

**Table 2.** Farmer and farm characteristics of the total sample of farmers

Farmer Characteristics:	
Gender	12% Female 88% Male
Role on the farm	64% I am the titleholder/owner 18% I am an unpaid relative of the titleholder 5% I am a paid relative of the titleholder 7% I am an employee 5% Other role on the farm
Principal or main origin of agrarian training	32% Agricultural university training 39% Agricultural vocational training 18% Courses, conferences, workshops, etc. 12% (only) Practical experience
Farm structure:	
Farm area	24% Less than 25 ha 27% 25 a 50 ha 8% 26 - 75 ha 14% 76 - 100 ha 26% More than 100 ha
Farm soil fertility	11% low 19% neutral 70% high
Water supply problems	2% Always or almost always 7% Many times 27% Few times 65% Never or almost never
Is farms located in a vulnerable area due to nitrate contamination?	50% Yes 44% No

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	6%	I do not know
Technologies or innovations implemented on the farm:		
Farm innovation adopted (last 10 years)	20%	Not Adopted
	80%	Adopted

**Table 3.** Farmers' preference for sustainable activities

Preferences for sustainable objectives (analytical hierarchical process):				
Sustainable objectives:	Individual farmers' preferences	Normalized Local weight	Normalized Global weight	Action
Economic	19.17%	12.1%	7.9%	Diversify the production & marketing channels
	12.50%	14.2%	9.3%	Increase the sales of the farm products
	35.83%	73.7%	48.2%	Maximize the net profits of the farm
Social	4.17%	32.5%	0.9%	Employment creation in the area
	1.67%	31.2%	0.9%	Prevent depopulation of rural areas
	5.00%	36.4%	1.0%	Preserve existing socio-cultural values
Ecologic	5.83%	26.9%	8.5%	Reduce polluting emissions
	7.50%	36.8%	11.7%	Maintain soil fertility
	8.33%	36.3%	11.5%	Rational use of water

**Table 4.** Farmers' willingness to adopt sustainable innovations

Specific Innovations Acceptance: Opinions about sustainable innovations proposed		
Farmers' general opinion about innovation	69.6%	Think it could be interesting
	8.1%	Think it's not very useful
	11.1%	Think it's not feasible
	7.4%	Think it is too much work for little result
	3.7%	Other.
Willingness to adopt innovation	47.8%	Yes or probably yes
	21.6%	Do not know
	30.6%	No or probably not
Opinions of farmers who don't plan to adopt	35.2%	No matter the initial investment
	36.1%	No matter the profit increase
	40.6%	No matter % of Emissions reduction
	37.0%	No matter the payback period

Table 5 below shows the difference between adopters and those farmers who did not adopt any innovation in the past ten years in terms of their demographic and personal characteristics, economic attributes of their farm enterprises, as well as physical and geographic characteristics of farms. The population of adopters consists almost exclusively of male farmers. Younger farmers <35 years are less likely to be adopters while 45 to 65 years of age are more likely to adopt. The survey data on agricultural training show a highly heterogeneous picture across the two groups of farmers. While adopters have a slightly higher proportion of those with a university degree, the percentage of farmers with practical experience is higher among non-adopters. Also, a higher proportion of

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farmers with adoption experience tend to attend various courses, conferences, and workshops to improve their training. Both groups have approximately equal proportions of farmers with vocational training. Turning to association memberships, the proportion of active members is almost twice as high among adopters than among farmers without adoption experience. Almost a third and a half of all adopting farmers are members of either producer associations or agrarian unions respectively, compared to just 14% and 24% of non-adopters. It is worth noticing that a higher proportion of adopters is solely employed in agriculture, which implies that they have more time to specialize in farming.

In terms of structural economic attributes, Table 1 shows a bigger portion of innovative farms belonging to vertically integrated companies, which may simplify their access to technologies and capital of those firms. Similarly, adoption-prone farms tend to rely more on the borrowed capital relative to non-adopting producers. Additionally, they differ in terms of how they use this capital to finance their activities. For example, adopters tend to invest in construction or purchase machinery and equipment, while non-adopters borrow more liquidity to finance day-to-day operations. When it comes to agricultural insurance, on average nine out of ten adopters have some sort of insurance compared to seven non-adopters. They also tend to diversify their marketing channels by selling to more clients compared to non-adopters. Comparing both groups based on a farm area, it can be further shown that farms without any recent adoption history are smaller compared to more active farms. For example, a proportion of adopting farms with acreage above 75 ha is higher than that of non-adopters. Farm's acreage might be a decisive factor of technology adoption as bigger farms can borrow more capital while using their land as collateral. Finally, both groups are not visually different in terms of the quality of arable land. The farmers' subjective estimate of land fertility is slightly above six (on a 10-point scale), while the degree of erosion is below three, signifying that the farmers in the sample on average manage good quality land. The surveyed farms also tend to be located rather close to larger settlements.

**Table 5.** General characteristics of adopting versus non-adopting farmers

Factors	Adopters (N=118)	Non-adopters (N=29)
<b>Gender</b> (% of males)	91.96	72
<b>Age</b> (%):		
<35 yo	19.09	36
35-44 yo	20.91	20
45-54 yo	23.64	16
55-64 yo	23.64	16
>=65 yo	12.73	12
<b>Agricultural training:</b>		
<i>agricultural university</i> (%)	33.04	28
<i>practical experience</i> (%)	54.46	72
<i>vocational training</i> (%)	38.39	40
<i>courses/conferences/workshops</i> (%)	43.75	24
<i>multiple training activities</i> (%)	2.68	4
<b>Association membership</b> (%):	67.8	37.93
<i>producer association membership</i> (%)	33.9	13.79
<i>agrarian union membership</i> (%)	48.31	24.14
<i>environmental NGO membership</i> (%)	4.24	0
Solely employed in agriculture (%)	67.8	48.28
Part of a vertically integrated company (%)	25.42	13.79
% of farms in debt:	61.02	41.38
- loan to invest in construction (%)	70.83	50
- loan to invest in machinery/equipment (%)	59.72	41.67
- loan to cover operational expenses (%)	16.67	25
Ag. insurance (%)	86.44	72.41
Number of main clients	3.12	1.46
<b>Farm area</b>		
<= 25 ha	24.58	21.43
26-50 ha	22.03	28.57
51-75 ha	9.32	21.43
76-100 ha	11.86	7.14
>100 ha	32.2	21.43
Fertility of land (10 is max)	6.36	6.17
Degree of erosion (10 is max)	2.63	2.45
Distance from a large settlement	1.59 <sup>1</sup>	1.96 <sup>1</sup>

<sup>1</sup> This distance on average is below 10 km



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Review

# Factors Influencing Adoption of Sustainable Farming Practices in Europe: A Systemic Review of Empirical Literature

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**Abstract:** Modern practices of industrial farming, such as mineral fertilization, caused a widespread degradation of agricultural land and water bodies in Europe. Different farm management strategies exist to reduce the impact of mineral fertilization while preserving soil productivity. The aim of this paper is to provide a thorough systemic review of contemporary literature exploring factors and conditions affecting EU farmers' adoption of sustainable farming practices. The specific focus is on widely adopted and empirically explored measures, such as organic farming, manure treatment technologies and manure fertilization, as well as soil and water conservation methods. In total, 23 peer-reviewed studies were extracted by means of Google Scholar covering the time period between 2003 and 2019. The main findings show that farmers' environmental and economic attitudes in addition to their sources of information have a strong effect on the adoption of organic farming, although there is a lack of evidence of their impact on adopting manure treatment and conservation measures. Similarly, farmers' age and education are found to systemically influence organic farming adoption, but not adoption of other reviewed technologies. While other factors, such as farm physical characteristics or technological attributes, may be important determinants of adoption, it is hard to recognize definite patterns of their impact across technologies given a shortage of empirical evidence. More research utilizing standardized surveys and methods of analysis is needed to formulate qualified guidelines and recommendations for policymakers.

**Keywords:** organic farming; manure treatment; conservation agriculture; animal waste; adoption factors

## 1. Introduction

Intensification of agricultural production in the past century across EU countries has seriously undermined the sustainability of the farming sector, resulting in widespread degradation of key environmental resources, such as land and water. One pernicious side effect of intensified farming is a nutrient surplus, which is defined as a positive difference between the amount of nutrients added to the soil (e.g., via fertilization) and the amount of nutrients taken or removed [1]. Despite some recent reductions in fertilizer application, the total inputs of key nutrients, such as nitrogen and phosphorus, still considerably exceed the soil absorption limits [1,2]. Additionally, the efficiency of the application of these nutrients remains extremely low [3]. Due to the high nutrient concentration, part of that surplus may be washed off from soil by heavy rains, causing environmental problems [4]. Another risk arising from high nutrient levels in soil relates to mineralization and an increased loss of organic carbon. It is reported that 45% of European soils experience infertility due to severe carbon deficits [5].

Reducing nutrient surplus to environmentally sustainable levels is crucial for achieving the aims of the Common Agricultural Policy [6]. The long-term effects of controlling soil nutrient levels may include improved agricultural productivity, soil fertility and biodiversity, which are important to ensure the stability of future food supply. The nutrient surplus reduction strategies are based on a combination of measures aimed at the preservation of soil structure and increasing nutrient and water use efficiency [7]. In addition, an important part of optimizing nutrient flows, stocks and emissions is through improved recyclability and reduced waste of animal by-products, such as manure [8].

There is ample evidence of the positive effects of organic farming, manure treatment and manure-based fertilizers and soil and water conservation on agricultural production and soil qualities. For example, conservation measures are shown to increase plant fertilizer uptake [9] and reduce surface water run-off [10], which is crucial to retain nutrients in soil and reduce the need for imported minerals [11]. Similarly, nutrients from recycled manure may substitute for chemically produced analogues [10]. Organic farming is an alternative farm management system combining various conservation measures and manure-based fertilization, while prohibiting application of mineral fertilizers. As a side effect of reduced reliance on chemical fertilizers, farmers may increase their resistance to external economic shocks (e.g., volatility in energy prices).

Previous literature reviews exploring factors of farmers' adoption of sustainable practices focused primarily on conservation technologies. For example, Knowler and Bradshaw [12] reviewed adoption studies of conservation tillage, crop rotation and cover crops in developing countries and North America, summarizing both the direction and significance of statistical effects of adoption factors. In a similar paper, Wauters and Mathijs [13] performed a meta-analytic review of factors affecting the adoption of conservation measures in the U.S., Canada and Australia. Furthermore, Carlisle [14] narratively reviewed determinants of adoption of various soil health practices in application to agricultural commodity production in the U.S. We extend these reviews by focusing on recent adoption studies of soil and water conservation in Europe, while also complementing them with a review of factors affecting adoption of organic farming and manure treatment technologies. Adoption of agricultural technologies in Europe might differ from other locations due to specific regulations, customs and natural conditions.

To the best of our knowledge, there are just a few examples of literature reviewing factors of adoption of sustainable farming in Europe. For example, Lahmar et al. [15] provided a general (non-critical) overview of drivers and constraints of conservation agriculture development in such countries as Italy, Spain, France and Czech Republic. Separately, Prager and Posthumus [16] reviewed determinants of adoption of soil conservation measures in several EU countries, using responses to standardized farmer surveys. Liu et al. [17] also mentioned several European studies in their review of factors of farmers' adoption of best management practices aimed at the reduction in non-point source pollution. In the most recent case, Dessart et al. [18] provided a policy-oriented review of behavioral factors influencing the adoption of various sustainable farming practices in Europe, such as organic farming and conservation agriculture. While this paper covers several studies also mentioned in our review, it focuses exclusively on behavioral factors of adoption such as farmer attitudes while disregarding other common determinants of adoption (e.g., farmer demographic attributes). Additionally, it covers studies on adoption of agri-environmental schemes, which is beyond the scope of the given review.

Given this background, our study pursues two main goals. First, it is to provide a brief overview of key regulations stipulating adoption of sustainable agriculture practices in Europe. Most of these regulations are in the form of mandatory directives, which might have a strong influence on the adoption and development of sustainable farming strategies. The knowledge of actual legislation is important to understand the differences in approaches to sustainable agriculture in Europe versus other areas. The second goal is to provide a comprehensive and systemic review of factors influencing farmers' decision to adopt three specific technologies directly contributing to a reduction in mineral fertilization rates and normalization of soil nutrient balance, namely organic farming, manure treatment

and manure-based fertilizers, and soil and water conservation (we ignore other popular themes of sustainable agriculture, such as integrated pest management, precision agriculture, genetically modified crops or agro-environmental schemes). To achieve this goal, a systemic and up-to-date review of empirical literature in Europe at the farm level is provided. We initially review key theories explaining fundamental principles behind farmers' adoption behavior. Exercising this knowledge, we categorize all adoption factors into thematic groups and analyze their effects on farmers using reported summaries of statistical analysis or general survey results. We retrieve the direction of effects and their statistical significance from all studies based on regression analysis. Additionally, we aggregate reported marginal effects from studies based on non-linear regression analysis to estimate an overall size of the statistical effects of key adoption factors across different technologies.

## 2. Methodology

### 2.1. General Structure

The structure of this paper is organized as follows. It starts from the Methodology section which includes information about the selection of empirical literature and aggregation of marginal effects of the main adoption factors extracted from the literature. Subsequently, a review of relevant regulations at the EU level affecting farmers' adoption strategies is provided to give the political and legislative context in which farmers make adoption decisions. This is followed by a general overview of the theoretical foundations of technology adoption behavior. A section reviewing empirical studies of adoption factors in Europe for each technology group—a central part of this paper—is presented next. In the end, conclusions are given to summarize the main findings of the empirical review.

### 2.2. Search Terms and Selection Criteria

To identify relevant studies for the empirical review, we initiated a search through Google Scholar using various combinations of key English words depending upon the technology in question. For example, to find studies on organic farming, we typed "Organic farming adoption" in the search field, while for conservation agriculture studies, we successively tried two search combinations: "Farmer conservation adoption" and "Conservation agriculture technology". Additionally, we used three combinations of specific terms to find studies on manure treatment: "Manure treatment adoption farm survey", "Manure treatment technology adoption" and "Manure utilization technology". The choice of search words was based on the vocabulary used in previous reviews and industrial reports.

As a result, 200 different items were identified for each search combination used, yielding initially 1200 titles in total. To capture recent trends in the technology adoption literature, we imposed strict time constraints focusing specifically upon those items published in between 2003 and 2019. All the titles that passed through the time filter were further checked for compliance with the geographical criteria and the type of literature. As a result, we dropped all studies unrelated to the European Union or the EFTA area (the European Free Trade Association states are Switzerland, Norway, Liechtenstein and Iceland; these are not EU members, but it is fair to treat them as part of a common agricultural area) and only selected peer-reviewed journal publications while ignoring conference papers, industrial reports and other types of gray academic literature, which narrowed the selection pool to 33 items. At the final stage, a cursory review of the publications was performed to understand if they pertained to relevant technologies and if the analysis was based on farmer survey data. After removing items not conforming with the above-mentioned filters, we arrived at the pool of 23 publications that formed the basis of the empirical literature review. Figure 1 provides a summary of the selection process.

Overall, 11 selected studies explore adoption of organic farming, 7 studies focus on manure treatment technologies and 5 studies cover conservation farming (Table S1). Most of the selected studies use econometric techniques to analyze data from farmer surveys, while a handful of studies provide a general summary of survey results without applying any quantitative methodology. While not all EU countries are covered by the selected studies, this review is still geographically diversified, representing

all main areas except for some countries of Central and Eastern Europe. Nordic (also known as Scandinavian) and Benelux countries are mentioned 11 times, while there are 7 studies from the south and 4 from the west-central part of the EU. Furthermore, there are 6 studies from the UK and Ireland, and 2 studies from Baltic countries (Figure 2).

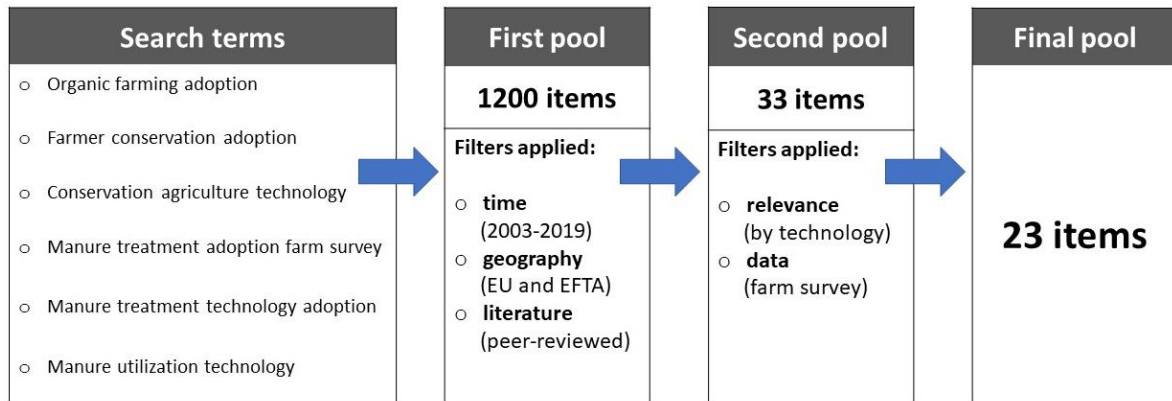
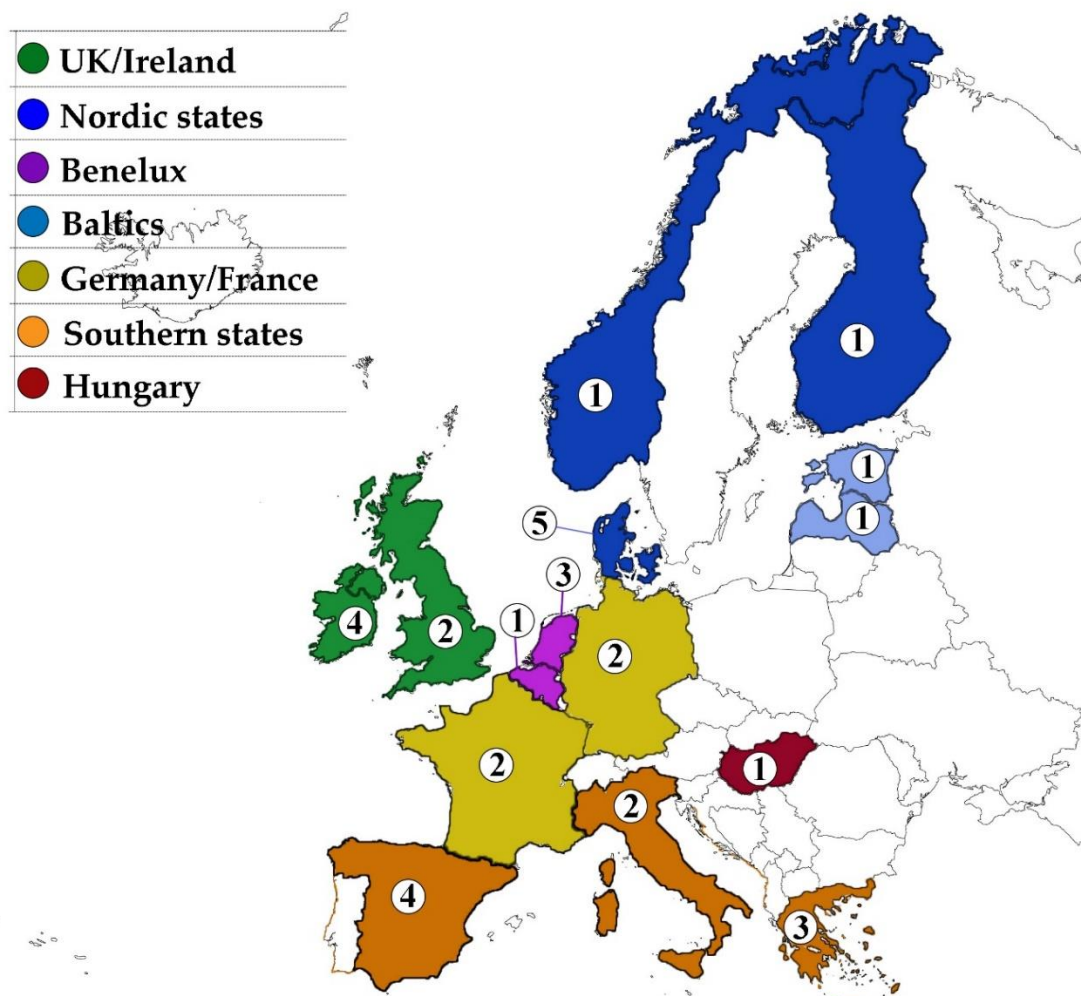


Figure 1. Diagram of the main selection steps.



Note: circles on the map contain the number of studies recovered for each country

Figure 2. Map of European areas included in the review.

### 2.3. Marginal Effects of Adoption Factors

To summarize the impact of the selected adoption factors across different technologies, we aggregated their marginal effects, using the reported information from empirical studies based on non-linear regression analysis, such as probit or logit models. In contrast to regression coefficients, which cannot be directly compared due to scale issues, it should be possible to compare the impact of adoption factors from different studies using their marginal effects, which measure the marginal probability of a change in an adoption variable with respect to a change in a covariate (adoption factor) [19]. To show how some key factors affect the probability of adoption of sustainable technologies, we constructed two simple statistics based on the reported information: mean and range. The former measure is a simple average of the collection of marginal effects, estimated as  $\frac{1}{N} \sum_{i=1}^N x_i$ , where  $x_i$  is a value of a marginal effect from study (population)  $i$ , while the latter represents an interval of extreme values of these effects for a specific covariate. All data manipulations and measurements were performed using Microsoft Excel and Stata, which is a popular statistical software for data science [20].

## 3. EU Regulations Relating to Sustainable Agriculture

Technology adoption in the EU agricultural sector takes place in a highly regulated environment. The EU-wide regulations are complemented and enhanced with national and regional laws and policies. Research provides ample evidence of the impact of various policies and regulations on technology adoption and innovation diffusion in agriculture [21–23]. To provide a background for technology adoption by farmers, we review key EU-level regulations affecting the adoption of organic farming and manure treatment technologies, as well as soil and water conservation practices.

A critical set of rules and regulations, the Common Agricultural Policy (CAP), outlines the conditions of public support to EU farmers in the form of direct subsidies (Pillar 1). An additional function of CAP is support of rural development known as Pillar 2 [24]. Initially designed to stimulate agricultural output, the policy underwent a substantial transformation in the last twenty years towards a more environmentally oriented legislation. Specifically, the last big reform in 2013 introduced “greening payments” linking the allocation of subsidies to farmers’ compliance with certain conservation rules. These rules include maintaining permanent grassland, crop diversification and maintaining ecological focus areas such as field margins, hedges, trees, fallow land and buffer strips [25].

General priorities of rural development in the EU, including actions affecting agricultural ecosystems, are outlined in Regulation No 1305 [26]. The specific focus of this regulation is on restoring, preserving and enhancing biodiversity and high-value farming, as well as improving water management and fertilizer and pesticide management, and preventing soil erosion and improving soil management. A related objective of this regulation concerns the promotion of resource efficiency and support of the shift towards a low-carbon and climate-resilient economy. A special section outlines the terms of financial support for the farmers who convert to or maintain organic farming practices.

Another piece of legislation affecting organic farmers is Regulation No 834 [27], which explicitly defines the objectives, principles and rules of the production, processing and distribution of organic products. The rules of organic production affect both crop and livestock farmers. The former, according to the regulation, must employ cultivation practices that enhance soil stability and biodiversity while preventing soil compaction and erosion. No mineral fertilizers should be used to maintain soil productivity. The latter are prescribed to implement housing conditions and maintain stocking densities observing the developmental, psychological and ethological needs of animals. Specifically, livestock density should be restricted to minimize overgrazing, poaching and soil erosion. The correct conversion rules also prescribe the reliable separation of organic and conventional agricultural practices [27].

A separate set of directives regulate soil and water conservation measures. The directive No 676 [28] was enacted to promote the identification of vulnerable zones accumulating nitrogen from fertilization. The directive specifies recommendations to reduce fertilization on steep slopes, as well as on water-saturated, flooded or snow-covered ground and near the watercourse. To prevent water pollution from livestock manure, it is recommended for farmers to consider construction of storage

vessels. The directive's mandatory action program introduced limits on the amount of nitrogen applied to the soil. The directive No 278 [29] regulates the application of sewage sludge in agriculture. According to this directive, it is prohibited to use sewage sludge if the accumulated levels of heavy metals in it exceed the permitted limits. Application of sewage sludge is also prohibited on certain types of land, such as grassland.

Finally, the directive No 60 [30] provides a general framework for maintaining and improving the aquatic environment in the EU. Concerning its impact on agriculture and farming, this directive contains the indicative list of main water pollutants of agricultural origin including biocides and plant protection products, in addition to substances contributing to eutrophication. The recent Thematic Strategy for Soil Protection [31] provides a framework for a future directive aimed at the protection and sustainable use of soils in the EU. The strategy is based on two guiding principles: preventing further soil degradation and preserving its functions, as well as restoring the functionality of degraded soils.

As of manure treatment regulations, the above-mentioned directive No 676 [26] contains rules regarding the capacity of storage vessels for livestock manure. Specifically, it is prescribed to build larger vessels in excess of the required storage capacity if immediate discharge is prohibited due to the presence of a vulnerable zone. According to the directive, exemptions to this rule may apply when farmers can demonstrate that manure disposal causes no harm to the environment. The regulation No 1069 [32] stipulates rules for the collection, transport and disposal of animal manure. The disposal rules specify that animal manure can be disposed of as waste by incineration, recovered or disposed of by co-incineration, disposed of in an authorized landfill or used as an input to manufacture organic fertilizers or soil improvers, as well as being composted or transformed into biogas. According to the regulation, farm operators must seek approval from the competent authority for the construction of plants to manufacture organic fertilizers and soil improvers, or to transform animal by-products into biogas or compost. The regulation also specifies criteria for putting organic fertilizers and soil improvers on the market.

#### 4. Theoretical Foundations of Technology Adoption

The conceptual foundations of technology adoption in agriculture are rooted in the social psychology theory. One prominent example is the theory of planned behavior (TPB), originally developed from the theory of reasoned action [33]. TPB defines human actions as a direct function of people's intentions and the degree of their perceived behavioral control [34]. According to Ajzen [34], people's intentions to perform behaviors result from both their personal attitudes towards the planned action and from the subjective norms representing the perceived social pressure to perform or not to perform the behavior. Behavioral control refers to people's perception of the ease or difficulty of performing the behavior of interest. Ajzen [35] noted that perceived control can define people's behavior directly or through the formation of intentions. According to the theory, people regularly revise their salient beliefs underlying the formation of attitudes, subjective norms and behavioral control in response to the outcomes of behavior. While people's intentions may predict their actions, they often diverge, leading to a so-called intention-behavior gap, which was recently explored in the context of farmers' production plans in the EU [36].

A conceptually similar model to TPB is the transactional model of human behavior adapted by Willock et al. [37] to study farmers' behavior. The three building blocks of this model are antecedents, mediating variables and outcome variables [37]. Antecedents refer to the basic qualities of personal character, human attitudes and the attributes of the environment. Mediating variables represent cognitive constructs describing people's aspirations, objectives or intentions, while outcome variables are closely associated with actual behaviors. In contrast to TPB, the antecedent variables of the transactional model can directly affect people's behavior while simultaneously contributing to the formation of people's objectives. Willock et al. [37] argued that farmers can recursively modify their objectives in response to the arrival of information about the outcomes of their behaviors.

Both afore-mentioned theories indicate that people's attitudes and preferences might be critical determinants of their behavior. Fishbein and Ajzen [33] described attitude as a learned proclivity to respond in a consistent way towards a given object. A broad set of environmental, social and economic attitudes may direct farmers' behavior. In a comprehensive study of farmer behavior in Scotland, Willock et al. [37] showed that such attitudes as openness in farming and the attitude towards chemical use correlate well with the farmers' propensity to adopt an environmentally sustainable behavior. Empirical studies show that attitudes relating to profit orientation and environmental concerns are two forces driving farmers' adoption of organic production [38,39].

A separate theory describes the farmers' technology adoption process through the acceptance criteria proposed by Esser [40]. According to this approach [41], farmers' technology acceptance is determined by the subject of acceptance, the object of acceptance and the surrounding context or framing conditions. The subject of acceptance refers to the farmers' personal characteristics and their attitudes and preferences regarding the object of acceptance. The object of acceptance concerns the attributes of the technology itself such as the cost of implementation, estimated benefit, time requirements and risks. Finally, framing conditions represent various circumstances surrounding technology adoption such as the farm's financial state, the political environment and governmental policies and regulations.

Technological adoption results from a constant innovation process transforming ideas into new or improved products, services or processes [42]. Based on the theory of diffusion of innovations, technological attributes are crucial to the adoption process. Within this approach, Rogers [43] classified innovation attributes consisting of relative advantage, compatibility, complexity, trialability and observability. Relative advantage refers to the superiority of the current innovation over its past version. Compatibility defines the degree to which the innovation is consistent with socio-cultural values and beliefs, previously introduced ideas or client needs for innovations. Complexity of innovation determines if it is perceived as difficult for understanding and further implementation. Trialability shows if the innovation's implementation can be divided in separate instalments. Finally, observability can be defined as the visibility of the results of an innovation.

Both trialability and observability are important attributes defining the dynamic nature of an adoption process. Emphasizing this idea, Pannel et al. [44] argued that technology adoption can be broken down into a set of consecutive stages: awareness of the problem or opportunity, non-trial and trial evaluation, adoption and non-adoption or dis-adoption. According to Pannel et al. [44], farmers go through these stages as they continuously learn and update their information on the technology adopted. Chatzimichael et al. [45] identified two ways through which farmers can acquire new information. In the first case, they learn by implementing the adoption process itself, while in the second case, learning occurs because of communication with other farmers, researchers and extension agents. Pannel et al. [44] argued that in the early adoption stages, uncertainty surrounding the new technology is often high, prompting farmers to rely upon their communication networks. Upon the start of trialing, farmers gain a unique hands-on experience of technology adoption which affects their future decisions.

Whilst the theory provides a useful framework for the classification and analysis of the technology adoption process, it may be too rigid to account for subtle differences in farmers' behavior across various localities and practices. To shed more light on the specific determinants of farmers' adoption behavior, it is important to consider empirical studies exploiting flexible instruments of data collection such as surveys and questionnaires. Using theory as a basis, we will classify the reported adoption factors into six thematic groups, namely farmer and household characteristics, farm structure and financial state, farmer individual attitudes and beliefs and their sources of information and communication channels, as well as technological attributes and attributes of the legal/institutional environment (which includes laws, regulations and incentives). Based on this classification, we will provide a systemic summary of the impacts of individual factors on the adoption of selected farming technologies.



## 5. Empirical Studies on Technology Adoption at Farm Level in the EU

Many innovative practices are available for EU farmers to improve soil nutrient cycles, reduce pollution and ensure sustainable food production. However, many factors and characteristics determine the adoption of such measures. The goal of this empirical review is to analyze key factors and conditions affecting the adoption of organic farming, manure treatment technologies and manure-based fertilizers, in addition to soil and water conservation measures. A brief summary of the reviewed studies is available in Table S1, while the impact of adoption factors across various technologies is summarized in Table S2.

### 5.1. Organic Farming Adoption

Organic farming is a prolific topic in the technology adoption literature. It is defined as a method of agricultural production encouraging application of natural substances and processes to limit the industry's negative impact on the environment and society [46]. To be certified as organic, EU farmers must adopt certain measures to maintain and improve the quality of soil and water and ensure a high standard of animal welfare. For example, the EU organic rules prescribe the application of livestock manure and multi-annual crop rotation to maintain the fertility and biological activity of soil [47]. Based on 2016 statistics, more than 185,000 farms across the EU converted to organic farming, which amounted to 6.2% of the bloc's total utilized agricultural area in 2016 [48]. It is expected that this figure will increase to 25% by 2030 as part of the new EU green deal [49].

Altogether, this review summarizes findings from eleven studies covering organic farming adoption in ten countries, which represent various climatic zones and agricultural conditions in Europe (Tables 1 and S1). Among the countries in Table 1, only Benelux states, in addition to Hungary, are not covered in this section. Most studies use variations of probit or logit models to analyze survey-based data, with just a few examples applying duration analysis or agent-based modeling. In general, these models allow determining the conditional probability of adoption or the extent of diffusion of organic farming, given a variety of covariates. While the exact specifications may vary depending upon the geographic location, institutional context or researchers' choice of questionnaire, it is possible to aggregate the most common factors into several groups according to the theory of technology adoption.

**Table 1.** Key environmental and socio-demographic characteristics of reviewed countries.

Area	Country	Rainfall (mm/year) <sup>1</sup>	Temperature (°C) <sup>2</sup>	Aridity <sup>3</sup>	Elevation (meters) <sup>4</sup>	Agri land (%) <sup>5</sup>	Soil Erosion Risk (%) <sup>6</sup>	Age <sup>7</sup>	Education <sup>8</sup>
South	Spain	636	14.7	0.96	660 to 3718	52.5	26.87	56.5	1.9
	Greece	652	15.89	1.56	498 to 2917	47.6	29.13	60.9	0.6
	Italy	832	14.1	1.45	538 to 4748	43.24	52.41	65	6.1
UK/Ireland	Ireland	1118	9.87	4.73	118 to 1041	64.5	2.57	54.2	25.2
	UK	1220	9.11	4.09	162 to 1345	71.7	7.35	62	17.3
Nordic states	Denmark	703	NA	4.57	34 to 171	62	0.08	54.2	6.8
	Finland	536	2.2	16.84	164 to 1328	7.5	0.11	33.4	11.4
	Norway	1414	1.02	30.15	460 to 2469	2.7	NA	NA	NA
Benelux	Netherlands	778	10.26	2.84	30 to 322	53.3	0.08	47.7	9.4
	Belgium	847	10.34	3.40	181 to 694	44.6	4.57	48.8	21.3
West	France	867	13.77	1.63	375 to 4810	52.45	11.1	44.3	34.9
	Germany	700	9.02	6.92	263 to 2963	47.68	6.8	39.5	17
Baltics	Estonia	626	5.8	13.37	61 to 318	23.07	0.07	49.9	28.6
	Latvia	641	6.33	12.65	87 to 312	31.06	0.27	56.9	31.3
Center	Hungary	589	10.84	3.59	143 to 1014	58.36	9.57	58.1	4.4

**Notes:** <sup>1</sup> Rainfall data are the year average from 2014 records [50]. <sup>2</sup> Earth surface temperature is the year average over 2010–2012 records [51]. <sup>3</sup> Aridity is estimated as a ratio of monthly levels of precipitation to reference evaporation based on 2010–2019 data (lower values point to drier conditions) [52]. <sup>4</sup> Elevation (from mean to peak) [53]. <sup>5</sup> Agricultural land as a percentage of total land area [54]. <sup>6</sup> Percentage of agricultural areas and grassland subject to moderate-to-severe levels of soil erosion by water [55]. <sup>7</sup> Percentage of farm managers  $\geq 55$  years old [56]. <sup>8</sup> Percentage of farmers with full agricultural training [56].

### 5.1.1. Farmers' Demographic and Household Characteristics

The first group encompasses farmer demographic characteristics, in addition to household attributes. For example, age of the farm operator was found to be a significant determinant of organic farming adoption by five out of eight studies that included this covariate in the analysis. As the results show, older farmers have fewer chances of becoming organic relative to their younger colleagues, which might be an indication of dominating risk aversion among farmers nearing their retirement. Conforming to this perspective, the study by Chatzimichael et al. [45] empirically proved that age may have a non-linear impact on farmers' adoption behavior by showing that, up to a certain level, it may improve the odds of organic farming conversion. Another factor of adoption is the level of farmers' education. Similarly, eight studies included this variable in their analyses and five found a statistically significant effect on the likelihood of adoption. While most studies found a positive influence of education on adoption [45,57–59], one example showed the opposite effect [60]. In fact, Chatzimichael et al. [45] showed that, initially, education might be indeed beneficial to farmers, but more years of it result in the deterioration of their chances to turn organic. Similarities between the effects of age and education on farmers might be a direct result of how these covariates are constructed. The records of reviewed studies show that both factors are often proxied in terms of the number of years, which may cause collinearity between the two and also explain why, in the presence of education, the impact of age might be effectively muted and vice versa [39,60].

Apart from age and education, some studies also tested the impact of farmers' marital status, gender and household size on adoption decision. Both Burton et al. [60] and Tiffin and Balcombe [61] found that female farm operators have better chances of adopting organic farming compared to their male fellows, while Mzoughi [58] did not find the effect of gender significant. Marital status was analyzed by the only study and its effect turned out to be insignificant [59]. Four studies additionally analyzed the effect of household size on the propensity to become organic, but only one found a significant positive effect on it [38,39,60,61].

### 5.1.2. Farm Structural Characteristics

A second group of determinants of organic farming adoption concerns farm structural characteristics including such factors as farm size, livestock density, farm specialization and geographical location. For example, farm size has a significant impact on adoption, based on the results of four studies, while eight studies reported this aspect of adoption [38,39,45,57,59–62]. Regarding the direction of its effect, it was shown that farm size may both positively and negatively affect chances of adoption, which might reflect two contradicting views in the literature. According to one of them, farm size is just a proxy for farm financial strength, thus bigger farms have more resources to invest in sustainable technologies. An alternative view would imply that larger and financially more powerful farms will be reluctant to adopt organic farming to avoid potential negative consequences of this technology, such as yield uncertainty. Additionally, four studies reported the presence of off-farm income or an off-farm activity as adoption contributors [38,39,57,62], but only one study revealed a significant impact of such an activity on adoption [62], limiting possible broader generalizations. Further, two studies found evidence that proximity to urban areas increases chances for organic farming adoption [45,59], while two separate studies identified no significant impact of distance on the probability of adoption [39,57]. Occasional studies showed that such factors as aridity [57] or livestock density [38,39] might also affect adoption. Specifically, Genius et al. [57] found a negative effect of drier weather on organic farming adoption in Crete, which is a Greek island located in the Mediterranean Sea. Greece is one of the most arid countries in our sample, with an estimated cross-country aridity index of 1.56 (Table 1). In addition, 51.4% of its agricultural land is subject to a moderate-to-severe risk of erosion by water [51]. Given such an unfavorable climate, this area might benefit from subsidized cultivation and conservation initiatives, which are an important part of organic farming.

### 5.1.3. Farmers' Attitudes and Beliefs

A third group of factors includes farmers' beliefs and attitudes. In reliance with theory, there is a variety of attitudes affecting the probability of organic farming adoption. While interpretations of attitudes vary across studies, it is possible to categorize many of them in two large groups, namely environmental and economic attitudes. In the former case, "environmental attitude" [38,39] is also termed as "environmental awareness" [57], "environmental commitment" [58] or "environmental concern" [60], which all essentially imply a strong preference for environmental sustainability. One study provided no explicit definition of environmental attitude, but it is possible to derive similar meaning from its formulations of farmers' stated preferences for organic farming [59]. Overall, seven studies reported statistically significant evidence of some sort showing a positive relationship between environmental attitude and the inclination to develop organic production [38,39,57–60,62], while one study found no such effect [61]. Regarding economic attitude, it was similarly provided under various disguises, such as "profit orientation", "profit maximization", "cost cutting attitude" and others. Despite semantic differences, five studies showed that farmers' economic attitude associated with a preference for increasing the farm's profit and/or income negatively affects their odds to become organic [38,39,58,59,62]. In contrast, just one study found a statistically significant reverse effect [63].

Apart from these two attitudinal groups, some studies report the effect of farmers' risk preferences on their adoption chances. While some of them perceive risk attitude as part of the economic group of attitudes, the majority puts it in a separate category. In all cases, risk attitude is formulated either as risk aversion or risk hunger, which typically predetermines the direction of the effect. For example, three studies testing the effect of risk aversion found a negative impact of risk on adoption [38,39,58], while one study using risk hunger found an increased probability of becoming organic [62]. This generally confirms the widespread notion that riskier farmers are more prone to adopting new technologies.

### 5.1.4. Farmers' Sources of Information

A fourth group of factors broadly concerns farmers' sources of information. In contrast to attitudinal effects, it is hard to classify informational factors given their heterogeneous constructions across studies. For example, Läßle and van Rensburg [38] and Läßle and Kelley [39], two studies sharing similar data, found that various media sources such as TV and internet significantly depress farmers' chances to convert to organic production, while knowing other farmers may on the contrary help with this endeavor. The positive effect of communication with fellow farmers was in various forms, also identified by Burton et al. [60], Chatzimichael et al. [45] and Tiffin and Balcombe [61]. Five studies additionally reported the influence of an advisory service on farmers, with two showing the negative effect [60,61], one identifying the positive relationship [64] and the rest stating a lack of significant evidence of any relationship [38,39]. Moreover, Tiffin and Balcombe [61] and Burton et al. [60] both found that communication with buyers deteriorates farmers' chances for organic conversion. Professional membership was found to be negatively associated with technological adoption by Tiffin and Balcombe [61], while Burton et al. [60] did not find this relationship significant.

### 5.1.5. Institutional Environment

The last group of factors combines conditions of the institutional environment. Overall, three studies found an increased probability of starting organic production as a result of conversion subsidies [45,57,64]. Additionally, Kallas et al.'s [62] somewhat counterintuitive finding demonstrates that difficulty to get loans might actually induce adoption of organic farming. Another factor that this study found should positively affect adoption chances is farm location in a disfavored (less favored) area. A less favored area (LFA) is a legally defined area with conditions unsuitable for productive cultivation, such as mountains or low-soil productivity areas [65]. While this result was not properly discussed in the study, it is possible to attribute the impact of LFA on farmers' behavior to the allocation of compensatory allowances, which was a mechanism of farm income support in the less favored

regions of the EU. This is in line with similar research, showing the positive impact of compensatory payments on farmers' participation in the environmentally sensitive areas schemes [66]. Moreover, Kallas et al.'s [62] study focused on organic winemaking in Catalonia, where 56% of the region's agricultural area was classified as less favored due to its extremely dry climate [67]. Deserted soils in semi-arid regions of Spain were shown to benefit from various organic farming activities [68].

In summary, these studies show that farmer demographic characteristics, such as age and education, and household attributes, such as household size, might be strong determinants of switching to organic farming. Additionally, farm structural characteristics, including its own size, location relative to urbanized areas or specialization may also induce or discourage adoption. It is important to note that factors describing farm financial state were not adequately covered in surveys on organic farming. Likewise, farmers' personal attitudes about the environment and financial bottom line are found to be strong determinants of adoption, so are various sources of their information about organic farming. While the institutional environment might affect organic conversion through various financial mechanisms, it is not clear from the reviewed studies how laws and regulations shape the conversion process regionally.

### *5.2. Adoption of Manure-Based Fertilizers and Manure Treatment Technologies*

Structural changes, such as the emergence of large-scale farming and the intensification of livestock production, have resulted in an increased accumulation of animal by-products, including manure, on farms [69]. In terms of benefits to farmers, animal manure has potential as a valuable source of many macro- and micronutrients, including nitrogen and phosphorus. Within the EU, the amount of nitrogen in excreted manure was 5.65 million tons in 2017, and just roughly half of this amount was applied to soil [70]. Apart from yielding farmer benefits, the increased manure concentration on farms may result in detrimental effects for the environment. One such effect is air pollution in the form of emissions of methane, which is a strong greenhouse gas [71]. The detrimental effects of manure on soil and water are primarily related to the nitrogen and phosphorus run-off resulting from over-fertilization. Various technologies are implemented in the EU to mitigate the negative impact of animal manure on the environment, including manure separation, anaerobic digestion and slurry acidification, in addition to pelletizing and composting [72–74].

This review covers seven studies addressing the adoption of manure treatment technologies in ten countries of the EU. These countries cover large swaths of agricultural land in areas with diversified climatic conditions such as Scandinavia, Benelux, Western and Southern Europe, as well as Hungary. There were no peer-reviewed studies found on this topic from the UK or Ireland (Tables Table 1 and S1). While five studies applied econometric models to analyze survey data, two others took a more qualitative approach by simply summarizing questionnaire responses from adopters and non-adopters. Four analytical studies used variations of probit or logit models to determine the probability of technological applications, and one study applied linear regression to measure the impact of the chosen covariates on the predicted variables. Since qualitative studies cannot be directly compared to those applying prediction techniques, we explicitly separate their results in this report. As before, all common factors of adoption are aggregated according to basic theory.

#### *5.2.1. Farmers' Demographic Characteristics, Household Attributes and Farm Structure*

In general, there is limited empirical evidence of the effect of demographic attributes and household characteristics on the adoption of manure treatment across the EU. Two studies reported a significant impact of age on adoption of manure separation and manure-based fertilization [72,75]. However, in the former case, older farmers are less likely to adopt the technology, while in the latter case, the opposite is true. Gebrezgabher et al. [72] also tested the impact of farmer education and the presence of farmer successors on the propensity to implement manure separation, but this attempt yielded an insignificant outcome. Similarly scant is evidence of the effects of farm structural characteristics on adoption. Gebrezgabher et al. [72] and Case et al. [75] reported the effect of farm size, which

was determined an insignificant predictor of adoption in both studies. Additionally, these studies came to the conclusion that livestock density may significantly affect adoption chances, and adoption is more likely given an increase in density [72,75]. A third study reporting the effect of density on adopting various innovations in the horse sector found an insignificant result [76]. Further, Zemo and Termansen [77] showed that a farm's proximity to a bio-based plant increases farmers' willingness to invest in the plant, once again underlying the role of physical distance in defining adoption behavior.

#### 5.2.2. Farmers' Attitudes and Beliefs, and Sources of Information

Farmer attitudes and beliefs as adoption factors went essentially unnoticed by manure treatment researchers. Only the study by Rantala et al. [71] identified an impact of farmer individual valuations on technological adoptions by horse operators. Counterintuitively, their results show a negative significant effect of environmental valuations, but a positive effect of economic valuations on adoption decisions, which stands in contrast to the findings of organic farming researchers. This observation may point to the apparent disagreement between the definitions of most relevant attitudes in empirical surveys. Regarding the impact of sources of information on adoption, only Zemo and Termansen [77] explicitly showed that a start-up consultancy might positively affect the willingness of farmers to collectively invest in manure-based biogas facilities. Gebrezgabher et al. [72] additionally explored the effect of farmer knowledge of the relevant technology in general but found no evidence of statistical significance of this effect.

#### 5.2.3. Technological Attributes

Another group of adoption criteria deals with attributes of manure treatment technologies. According to this review, four studies in total mentioned multiple technological attributes as determinants of adoption. For example, Tur-Cardona et al. [78] found that the reduction in the price of organic fertilizer stimulates its dissemination on farms, whereas the uncertainty over the nitrogen content on the contrary reduces the likelihood of adoption. In a similar way, this study found that such attributes of organic fertilizer as a solid form and fast nutrient release in the soil motivate farmers' widespread application. In a separate study, Gebrezgabher et al. [72] identified a positive causal relationship between the potential adoption of manure separation and the factor combining various attributes of this technology, such as cost or fraction thickness. Zemo and Termansen [77] identified the terms of agreement between farmers participating in a collective investment in a manure-based biogas plant. Their findings demonstrate that farmers' willingness to participate in this project increases if they can prematurely leave the partnership. Finally, Hou et al. [74], using a simple summary of a farmer survey, showed that the increased price of a chemical fertilizer may stimulate farmers to switch to a bio-based alternative.

#### 5.2.4. Institutional Environment

There are also a few studies reporting the influence of institutional characteristics on the adoption of manure treatment technologies. For example, Zemo and Termansen [77] found that the subsidy to support the construction of a biogas plant should stimulate farmers into being willing to invest collectively in this project, while Hou et al. [74] reported pressure from policies and regulations as a possible determinant of adoption of various manure treatment technologies.

In the end, it is possible to conclude that there is little evidence showing the impact of basic demographic characteristics, household attributes, attributes of farm structure and farmer individual attitudes and preferences on adoption of manure treatment technologies, signifying the presence of an obvious gap in the empirical literature. On the other hand, it should be clear that more studies are desirable to further pinpoint which technological attributes, apart from those defined, drive farmers to adopt specific technologies of manure treatment.

### 5.3. Adoption of Soil and Water Conservation Practices

One of the implications of the intensification of agricultural production is soil degradation and water quality deterioration. Typical forms of soil degradation are linked to intensive agricultural practices including compaction, salinization, acidification, decline in organic matter and the loss of biodiversity [5]. Due to the interrelations of biological, physical and chemical processes in water and soil, it is common to observe the negative impact of soil degradation on water. An example is eutrophication resulting from the leaching of soil nutrients to water bodies. In response to the problem of soil degradation, various conservation practices are implemented across the EU such as reduced tillage, no-tillage and direct seeding, as well as soil covering, crop rotation and others [15]. Regarding water conservation, the implemented technologies include permanent grass, sediment ponds and riparian buffer zones, among others [79,80].

Despite the existing cases of conservation agriculture in Europe, the overall scope of technology adoption remains limited as compared to the U.S., Australia and New Zealand [81]. As a result, there are a few examples of academic research addressing the problem of farmers' adoption of conservation technologies. In the most recent review of literature covering farmers' adoption of soil conservation in Europe, Prager and Posthumus [16] concluded that a wide variety of environmental, economic, institutional and personal factors can motivate farmers to adopt conservation technologies. They noted that depending on the political and cultural contexts, adoption might be either fully voluntary or result from mandatory policies and incentive programs. Further to this review, we contribute to the literature by including more recent empirical studies exploring the adoption of soil as well as water conservation practices in the EU.

Specifically, this review comprises five studies covering four EU states, such as Ireland, Greece, Denmark and Spain (Table S1). These countries represent three areas with distinct environmental and socio-demographic characteristics (Table 1). No relevant publications were found with respect to Nordic states, Western Europe, the Baltics or Central Europe. Non-linear econometric models are implemented in four studies, while one study exploits a general farmer survey to retrieve qualitative information about factors of adoption. Three studies explore various adoptions of soil conservation and two studies focus on water conservation. Given the limited amount of empirical evidence, the results of this review should be treated with caution when making generalized statements or providing policy recommendations. Following the earlier adopted approach, all factors are aggregated in groups in accordance with technology adoption theory.

#### 5.3.1. Farmer Demographic Factors and Household Characteristics

In terms of demographic factors and household attributes, three studies explored the effect of farmer age on the probability of adoption [80,82,83], with only one study showing that older farmers have significantly lower chances to adopt a soil protection strategy [82]. Giovanopoulou et al. [82] also discovered a positive significant effect of higher education on adoption, while Rodriguez-Entrena and Arriaza [83] found that education in general has no impact on farmers but those farmers with special agricultural training might be more willing to adopt selected technologies. Additionally, the latter study identified a positive role of descendants in stimulating farmers to develop conservation agriculture [83].

#### 5.3.2. Farm Structural Characteristics

Several studies reported farm structural characteristics influencing farmer adoption decisions. For example, farm size was found to be a positive predictor of adoption by two studies [80,83]. Gachango et al. [80] also found that farms located on mid-steep slopes are more prone to adopting conservation schemes than those established on flat ground, while Rodriguez-Entrena and Arriaza [83] found that location in irrigation districts significantly increases the odds of implementing conservation technologies. Additionally, several studies explicitly identified a significant impact of farm financial

indicators on the likelihood of adoption. For example, Buckley et al.'s [79] finding shows a negative impact of higher gross margin on farmers' willingness to adopt a water conservation scheme, whereas Rodriguez-Entrena and Arriaza [83] demonstrated that more profitable farms are more likely to adopt soil conservation. While this result seems to be surprising at first sight, it might reflect distinctive environmental and climatic conditions dominating sustainable agriculture development in the countries under review. For example, Buckley et al.'s [79] study covered certain areas in Ireland, which is a humid country with a relatively flat terrain and good soil quality (Table 1). Conversely, Rodriguez-Entrena and Arriaza [83] focused on southern Spain (Andalusia), known for its arid climate contributing to high levels of soil degradation (the estimated proportion of soil under moderate-to-severe risk of erosion by water is 48%, which is well above the average rate in the country, see Table 1). Under such circumstances, Irish farmers might be unwilling to adopt conservation measures, fearing low returns on their investments (because more conservation does not seem to be improving soil quality much), while in Spain, adopting conservation strategies might be a sure option to increase both soil productivity and farm profitability.

### 5.3.3. Farmer Attitudes and Beliefs

Based on this review, farmer attitudes and beliefs may also affect their chances of adopting conservation measures. For example, two studies found that a strong preference for environmental protection stimulates adoption behavior [79,82]. Buckley et al. [79] additionally showed that a positive attitude over environmental regulation makes adoption of water conservation more likely. Further, Giovanopoulou et al. [82] found a similar effect of problem awareness on the probability of adopting a soil protection measure. On the contrary, the latter study reported that farmers perceiving conservation subsidies to be low are less likely to begin adoption. The effect of farmers' perception of subsidies as well as their attitude to fines and penalties was studied by Gachango et al. [80], but their results provide no significant evidence of the impact of these attitudes on adoption.

### 5.3.4. Farmers' Information Sources and Technological Attributes

There is limited evidence of the impact of farmers' information sources on the adoption of conservation practices in the area. Giovanopoulou et al. [82] found that membership in professional cooperatives makes it rather unlikely, while Gachango et al. [80] showed that farmers' awareness of ecological status and measures to reduce nitrogen and phosphorus run-off has no effect on adoption. Similarly, there is insufficient information on the effects of conservation technology attributes on adoption. For example, Rodriguez-Entrena and Arriaza [83] found that only applying a certain fertilization method makes adoption of selected soil conservation practices more likely, while other characteristics, such as number of plant varieties, plantation age and plantation density, are determined irrelevant for this purpose. In a separate survey, Carmona et al. [81] identified weed presence, pest incidence and lack of zero-till technology as inhibitors of adoption of conservation technologies, but they did not test the statistical significance of these effects on farmers. Concerning institutional factors, only one study explored this issue by testing the effect of conservation subsidies on adoption, which was found positive but insignificant [82].

Overall, it was found that basic characteristics of farmer household, farm structure, demographic attributes and farm financial results may affect decisions to adopt conservation measures, but the existing empirical evidence is rather scant and inconclusive. A similar argument is applicable to attitudinal factors shown to affect farmers in one case but producing no effect in the other. Finally, sources of information, technological attributes and institutional factors are covered very superficially in studies on conservation farming, which complicates analysis of their roles in farmers' decision making. Further research is necessary to fill this gap in the literature and provide qualified guidelines for policymakers.



#### 5.4. Aggregation of Marginal Effects

To analyze the impact of adoption factors across various technologies, we aggregate their marginal probabilities of adoption from multiple studies to construct two simple measures of an overall size effect: mean and range. Breen et al. [19] noted that marginal effects (probabilities) often reported alongside the main coefficients of probit or logit models are free from scale issues and can be used to compare the effects of typical covariates across different models and populations.

As shown in Table 2, we report aggregate statistics for marginal effects related to several adoption factors, such as environmental attitude, age, general education and farm size. Age and education are typically measured by the number of years or coded as a dummy variable (yes/no), which makes it possible to compare their effects on the probability of adoption across different studies. A similar argument applies to farm size, measured in hectares, and environmental attitude, which typically comes in two forms: as a dummy variable (important/not important) and as a principal component (which combines effects of different but related factors).

**Table 2.** Summary of marginal effects (probabilities) for selected factors.

Variable	# of Studies Reported	# of Values Extracted	Mean	Range	
				Total	Significant Cases
Environmental Attitude	10	6 (6)	0.1353 (0.1353)	[0.022 to 0.422]	[0.022 to 0.422]
Age	13	14 (12)	0.0255 (0.0339)	[−0.096 to 0.556]	[−0.096 to 0.556]
Education (General)	11	11 (6)	0.0637 (0.1256)	[−0.25 to 0.481]	[0.0015 to 0.481]
Farm Size	12	10 (5)	−0.0017 (0.0015)	[−0.08 to 0.095]	[−0.001 to 0.0035]

Analysis of variance (between-groups comparison):  $F = 3.69$  with  $p > F = 0.0258$

Notes: significant results for columns 3 and 4 are given in parentheses.

To construct aggregated measures, we primarily extracted results from studies using non-linear regression models, such as probit or logit, while discarding those applying duration analysis, linear regression analysis, agent-based modeling or qualitative approaches, which initially yielded 17 studies. Further, five studies using logit or probit models were also discarded due to marginal effects not being reported. As a result, there are between 6 and 14 extracted values of marginal effects depending on the covariate. Since some studies report marginal effects for several adoption populations (for example, one study does that for full and partial organic converters), the total number of extracted values sometimes exceeds the overall number of studies that reported them.

The summary results in Table 2 show that the average (mean) marginal effect of environmental attitude on the probability of adoption across six different population groups is 0.135, which means that a single standard deviation change in environmental attitude leads to a 13.5% increase in the likelihood of adoption. However, the range of reported effects is quite wide from relatively small (0.022) to substantial (0.422). Regarding the effect of age, it follows from Table 2 that the likelihood of adoption increases as farmers get older, and the average effect of age is even higher for significant cases. Additionally, there is a very wide interval covering both negative and positive values of marginal effects. To explore this result further, it should be noticed that the mean effect of age on adoption is spoiled due to the presence of an outlier from the study of Giovanopoulou et al. [82], who expressed age as a dummy variable *increasing* for younger farmers. After removing this study from aggregation, the upper limit of the interval reduces to 0.016, while the mean effect becomes  $-0.0136$  for both significant cases and the entire pool, which means that a unit increase in age makes adoption of sustainable agriculture 1.4% less probable. Furthermore, the average effect of education is positive and even higher for significant cases, while the interval for the significant pool is also free from negative values, meaning a positive effect of education on adoption. Finally, the average effect of farm size on adoption is quite small and negative for the entire pool but positive for significant cases. The interval of significant cases is also much narrower compared to the range of all cases. Basically, this result reflects existing confusion in the literature about the effect that farm size exerts on adoption of innovations. Visually,

it can be further shown that both environmental attitude and education exert a substantially higher influence on farmers' adoption chances than age or farm size (Figure 3). The multiple comparison test using one-way ANOVA also shows a significant difference between these factors at the 5% level (see the bottom of Table 2).

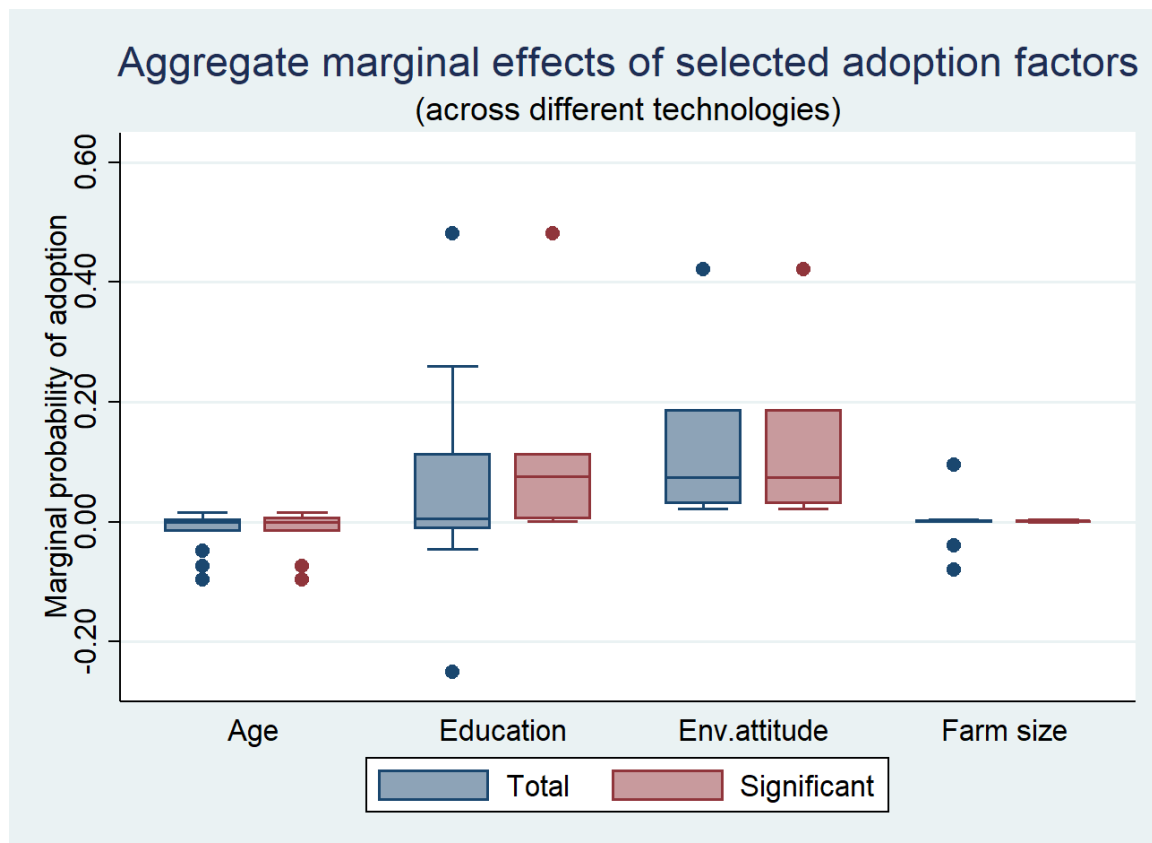


Figure 3. Comparison of aggregate marginal effects (probabilities) of adoption factors

## 6. Discussion

Reviewing empirical studies on farmers' technology adoption in the EU revealed a variety of factors having an impact on the adoption and proliferation of such technologies as organic farming, manure treatment and conservation measures. Following the theory of technology adoption, we classified all adoption factors into several groups, such as farmer demographic and household characteristics, farm structural and financial attributes, farmer attitudes and beliefs and sources of farmer information, as well as technological attributes and conditions of institutional environment. Altogether, 23 studies were recovered and reviewed, with eleven studies on organic farming, seven studies on manure treatment technologies and five studies about conservation agriculture. While all studies are based on farmer surveys, they used various methods to analyze data, with 16 studies applying non-linear regressions to estimate the probability of technological adoption. Due to the presence of these methods, it is often possible to aggregate the results of these studies based on both the significance and the direction of a statistical effect.

In general, it is hard to compare the effects of various adoption factors across the three technologies, given the obvious shortage of empirical evidence on manure treatment and conservation farming in the EU. While it is possible to track the effect of selected demographic attributes, like age or education, on organic farming adoption, their impact on the adoption of manure treatment and conservation farming remains rather dubious and inconclusive. Additionally, the impact of household characteristics on the adoption of sustainable agriculture remains largely under-investigated, with

just a few studies exploring the effect of household size or that of descendants. With respect to farm structural characteristics, it is shown that farm size might be a strong predictor of adoption of organic farming, with rather scant evidence of its impact on other technological adoptions. Other factors of this group, like distance to urbanized areas, might also influence farmer behavior, as follows from the selected studies covering various technologies. It is worth noting the evidence of the impact of farm financial state on conservation farming, which is absent from the studies on organic farming and manure treatment adoption.

Furthermore, farmer attitudes and beliefs are shown to clearly determine the adoption of organic farming in the EU, with environmental attitude stimulating adoption and economic attitude discouraging it. On the other hand, there is an absence of regular evidence of their impacts on both manure treatment and conservation farming adoption. Specifically, there is only one recent study exploring the impact of farmer attitudes on manure treatment and three other studies that investigate this aspect of adoption in application to conservation agriculture. Apart from attitudes and preferences, farmers may also formulate their adoption strategies under the influence of their sources of information, like media, an advisory service or other farmers. This conclusion follows mostly from the studies on organic farming adoption, although limited evidence exists proving the impact of informational sources on adoption of other technologies too.

Finally, this review found no systemic evidence of the impact of technological attributes on organic farming adoption, save for one study showing the positive effect of the market price of organic production. In a similar way, the price of organic fertilizer might be a predictor of adoption of manure fertilization methods, in addition to other physical and chemical characteristics of manure. While conservation farming attributes are mentioned in a few studies, they provide no systemic evidence of a statistically significant impact. Regarding the impact of institutional conditions, it was shown that adoption subsidies may induce the development of organic farming and manure treatment technologies in the area, but this effect is missing for conservation farming adoption.

## 7. Conclusions

Sustainable management of natural resources is one of the long-term aims of the Common Agricultural Policy, along with improved productivity and a stable supply of affordable food [6]. Given the challenge of attaining these aims, it is essential to maintain an efficient and circular production system based on the principles of increased recyclability of resources and waste minimization [8]. In agriculture, the decades of intensive use led to the degradation of critical resources such as land and water. Halting and reversing land degradation is crucial for mitigating hunger and achieving sustainable living [84]. Additionally, the efforts of sustainable resource management in agriculture should be focused on the treatment of animal manure to reduce waste and recover valuable nutrients [8].

Nutrient surplus is a common cause of land degradation in Europe, resulting from over-fertilization of soil with basic nutrients. The negative effects of excessive nutrient use include reduction in soil organic matter, stalled land productivity and water pollution. To deploy efficient nutrient reduction strategies, it is important to maintain a complex approach to land management based on the minimization of soil mechanical disturbance and measures improving nutrient cycles. Various conservation measures, such as reduced tillage, are shown to benefit soil and prevent water pollution. Additionally, technologies aiming to increase treatment and reduce waste of animal manure contribute to resource efficiency while reducing the need for mineral fertilizers, which is crucial for the development of alternative farm management systems like organic farming.

This review paper focused on various technological systems of sustainable farming in Europe, utilizing information and numerical data from peer-reviewed journal publications. While this methodological approach has its advantages, it also constrains the research to a narrow pool of selected results, which may not be fully representative of an entire research landscape (an issue known as publication bias). To mitigate this problem, it might be instructive for future reviews to consider other types of relevant output, such as conference papers or book chapters, covering different

geographical locations. Another problem emanating from the increased selectivity of literature sources is a shortage of numerical data, which limits the potential for a more profound statistical analysis. Provided more data on the statistical effects of adoption factors are available, it would be useful to recommend trying a meta-analysis involving regressions to disentangle the effects of geography or climate, for example. Finally, future research efforts may also consider reviewing other technologies of sustainable farming related to effective nutrient management, such as precision agriculture.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2071-1050/12/22/9719/s1>, Table S1: Summary of empirical studies on adoption of sustainable farming practices in the EU, Table S2: Impact of adoption factors across various technologies.

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