

Review Article

Assessing the Impact of Precision Farming Technologies: A Literature Review

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Abstract

Climate change, population growth, and economic shocks govern a context where food security and economic sustainability represent major challenges for the agricultural sector. Research for innovative production systems that ensure a better allocation of resources is a necessity to provide the foundations for farm reconversion. In this way, we carried out our work relating to precision farming, which is one of the innovative approaches aimed at ensuring the sustainability of agricultural production systems, thanks to its application principles and potential benefits. This synthesis paper examines aspects of assessing the impact of the use of such technology by analyzing previous research. The analysis carried out showed that the study of the impact of the use of precision technologies focused on three essential components on a micro-economic scale: the economic component, the environmental component, and the agronomic component. Prior studies examining the advantages of precision technologies have mostly relied on the examination of experiments and the application of quantitative analysis methods to measure the impact on environmental, economic, and agronomic parameters. The results of the study demonstrated that the adoption of precision farming technologies has provided advantages that contribute to the sustainability of agricultural production systems. Specifically, reducing environmental impact, cutting GHG (greenhouse gases) emissions by over 80%, valorizing natural resources (water and soil) with irrigation water savings of over 26%, and improving production efficiency and effectiveness. However, we suggest further studies examining the effects of precision agriculture using an integrated approach to assess the agronomic, economic, environmental, and social aspects of a production system as a whole. These studies will provide recommendations for adapting precision agriculture technologies to a wide range of farm types. In turn, highlighting the benefits of using precision farming technologies will support the process of adoption by farmers. The overview and findings presented in this article should point researchers in the direction of further research into precision farming technologies and provide extension staff, farm advisors, and farm machinery dealers with guidelines for promoting the adoption of precision farming.

Keywords

Precision Agriculture (PA), Assessment, Impact, Sustainability

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1. Introduction

Precision agriculture is a management approach for agricultural production systems [84]. It involves the use of various precision technologies to monitor and manage variability within fields through site-specific management [34].

Pedersen and Lind [66] have defined precision agriculture based on two complementary aspects: the technical aspect, where precision agriculture is associated with handling a high density of information and data referred to as "big data," which provide the presentation and interpretation of specific variables. Then the practical aspect, which pertains to the implementation of the results of big data processing in the field. Precision farming implies the existence of heterogeneity within a field and/or among fields, which requires variable-rate application of inputs in order to achieve production potential and economize agricultural inputs [22, 67].

In the definition by Pierce and Nowak [67], the concept of time has been properly introduced in addition to that of space. For them, precision agriculture involves managing the spatial and temporal variability of all agricultural production interventions through the combined use of modern technologies and scientific principles, with the aim of improving crop performance and environmental quality. In the literature, precision agriculture has the same meaning as site-specific management (SSM), the management of crop production systems, except that precision agriculture is a broader approach adapted to various production systems [66, 84]. Site-Specific Crop Management (SSCM) is an aspect of precision agriculture in which a set of technologies is associated to assist users in making decisions regarding input utilization and enhancing agronomic techniques that account for soil conditions and meet crop needs based on field variability [61].

Indeed, the potential benefits of adopting precision agriculture technologies revolve around the sustainability of production systems, through:

a. *Reduction of environmental impact and rational use of resources through:*

- 1) Improving the efficiency of machinery and agricultural input utilization [96].
- 2) Reducing pesticide residues in the nectar and pollen of flowering plants, thereby protecting the health of honeybees [54].
- 3) Contributing to increased biodiversity and pollinator populations through controlled use of chemical products [90].
- 4) Sustainable use of pesticides and fertilizers, through targeted application [46, 69].
- 5) Rational application of agrochemicals and minimization of environmental pollution risks [1-68, 69-96].
- 6) Mitigating the effects of climate variability.

b. *Optimizing agricultural production and improving incomes through:*

- 1) Improved management of agricultural practices using precision agriculture technologies [96].

- 2) Improved fertilizer and water efficiency per unit area managed [83].
- 3) Enhancing or preserving crop yields and farmers' income while optimizing input applications [1, 68].
- 4) Reducing production costs [1].
- 5) Improving product quality and traceability through technologies enabling precise field management (harvesting and sorting) to obtain a product with specific qualities [1, 31-68].

Technological advances provide a variety of tools and resources that contribute to the improvement of production management processes and the implementation of good agricultural practices. However, the rate of adoption of precision technologies is still low for certain categories [49]. Several factors influence the process of adopting PATs. Economic factors, such as the size of the farms, the complexity and cost of technologies, the availability of financial support [6, 30, 76], and other social factors related to the age of the farmers, their experience, and their level of education [30].

In addition, the adoption of PATs depends on farmers' perceptions of their usefulness [52]. Farmers expect the efficiency and effectiveness of input use (seeds, fertilizers, and pesticides) [63], the stability of their field productivity, increased farm income, and the optimization of natural resources (water and soil) [10]. This is how studies on the impact of precision agriculture provide farmers and decision-makers with data that will facilitate reasoning for the adoption of these technologies and potential interventions to support the development of precision agriculture.

In conclusion, emerging precision technologies promise to serve sustainable agriculture by enabling better allocation of irrigation water resources and reducing losses in fertilizers, all while exerting less pressure on natural resources.

In this context, some research related to precision agriculture technologies has been divided between studies focused on trials that assess the technical evaluation of precision tools in the fields [9-28, 38-50]. Other studies have addressed the assessment of the effects of precision technologies' application [70, 83-95] and other sources referenced in this paper.

The aim of this synthesis work is to analyze case studies related to the assessment of the impact of a set of precision technologies and to extract various aspects related to these studies. A clear and demonstrated understanding of the benefits offered by precision technologies enables farmers to make adoption decisions, gives adopters the opportunity to further improve their management, and provides the basis for decision-making related to incentives and interventions that can promote the transition to the precision farming approach.

Accordingly, this study aims to 1) Present the methodology adopted for selecting the articles for analysis. 2) Highlight the results of the impact of using precision agriculture technologies for production systems, while noting the approaches used by researchers to assess the benefits of PA technologies. 3) Pro-

vide a critical evaluation of the subject and recommendations.

The structure of this work will begin with a presentation of the methodology that explains the process behind performing this literature review. Following this, the results of the assessment of the impact of the use of precision farming technologies are outlined in terms of the three components: environment, economy and agronomy. Finally, the key findings and conclusions from this study are highlighted.

2. Methodology

The aim of this work is presenting a literature review of the literature on the impact of introducing precision agricultural technologies at farm level. The present study is the result of an analysis of a several research assessing the effects of implementing precision farming technologies in crop production processes. A deductive approach was followed to carry out this work and is described in [figure 1](#).

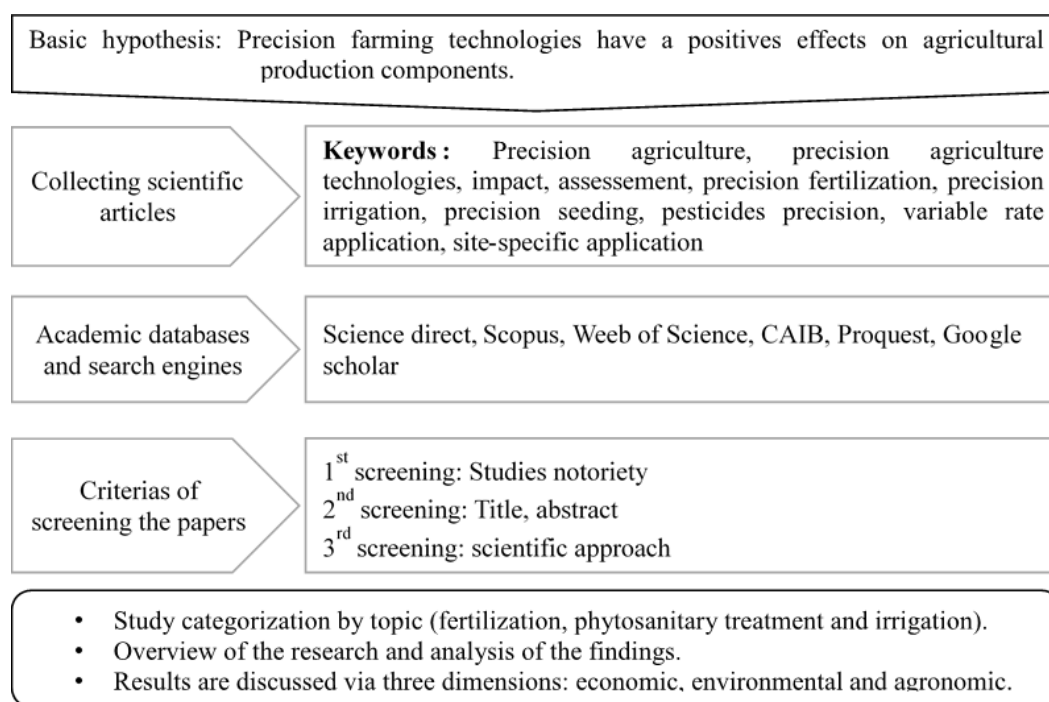


Figure 1. Review paper implementation steps.

3. Findings of Assessing the Impact of the Use of Precision Agriculture Technologies

One of the factors driving the adoption of precision agriculture technologies is the perceived benefits when these technologies are introduced into the production process. One of the factors driving the adoption of precision agriculture technologies is the perceived benefits when these technologies are introduced into the production process. Benefits including increased productivity, cost reduction, input savings, and reduced intervention time, influence the adoption decision among farmers [39, 74]. The quantified results of the effects of PATs help development actors to promote the adoption of these innovations [45].

In this section, we present the results of the evaluation of

the economic, agronomic, and environmental benefits arising from impact assessment studies of precision agriculture technologies (PATs) applied to crop production systems in different countries.

3.1. Agronomic Impact

Previous studies demonstrate the introduction of precision technologies in all agricultural interventions, including tillage, seeding, irrigation, fertilization, and pest control (Table 1). Additionally, the assessment of the benefits of precision farming has focused on field crops as well as arboreal species, allowing us to deduce the production systems where the use of precision technologies is most justified. In this section related to the analysis of the agronomic impact, we expect to demonstrate that precision agriculture technologies can increase productivity and improve yield quality criteria.

Table 1. Precision technologies assessed in research.

References	Cultivation	Technology	Application
[4]	Vineyard	Variable rate application	Fertilization Irrigation
[7]	Potato	Variable rate application	Nitrogen fertilization
[12]	Apple	Variable rate application Soil moisture sensors	Irrigation Nitrogen fertilization
[13]	Zucchini in a greenhouse	Decision support system Wireless soil sensors	Irrigation
[14]	Wheat	Laser levelling Precision seeding	Soil tillage Seeding
[21]	Potato	Proximity sensing (sensors)	Irrigation
[22]	Onion	Variable rate application	Irrigation
[24]	Barley	Variable rate application	Nitrogen fertilization
[27]	Potato	Proximity sensing (Sensor chlorophyll of the SPAD)	Nitrogen fertilization
[29]	Potato	Decision support system	Control plant disease
[40]	Wheat	Variable rate application	Nitrogen fertilization
[46]	Wheat	Laser levelling Precision seeding	Soil tillage Seeding
[70]	Wheat	Laser levelling	Soil tillage
[73]	Wheat	Variable rate application	Seeding
[77]	Soybeans	Geographic information system Irrigation strategy simulation model	Irrigation
[83]	Rice, wheat, mustard, sugarcane	Laser levelling	Soil tillage

3.1.1. Tillage and Precision Seeding

Precision soil leveling creates a favorable surface for crop development, where plants make efficient use of available resources (water and fertilizers), and thereby increasing productivity [83]. Ramadan et al., [70] achieved efficiency in wheat irrigation management using laser leveling with water savings of 40%.

Precision seeding technologies, in turn, bring benefits for farmers. They have the potential to optimize seed use and improve crop productivity. Samborski et al., [72] opting for variable-rate seeding of soybeans obtained an 18% reduction in seeding rate without affecting yield. According to Šarauskis et al., [73] doubling the sowing rate boosted wheat yields by 23% to 27% in regions where weeds were proliferating. Similarly, the integration of precision seeding and laser leveling technology has increased winter wheat yields by 23.2% [14]. The findings of research conducted in China [46] examining the impacts of laser leveling and precision seeding indicated that wheat was able to absorb more nitrogen, justifying a significant increase in grain yield by 22.51% and straw

yield by 34.51%.

Installing technologies like controlled traffic and automatic guidance systems on tillage equipment reduces field overlaps, which is expected to increase yield [4].

3.1.2. Variable Rate Fertilization

The Tekin study conducted in 2010 [81] in Turkey found that variable rate application increased wheat production by 1% to 10% while reducing nitrogen rates by 4% to 37%. The study conducted in 2013 by Biggar and al. in the United States regarding nitrogen fertilization based on sensor technology, revealed an increase of 5% in corn yield and 8% in wheat yield when nitrogen input was reduced by 21% and 10%, respectively [4].

Jovarauskas et al., [40] conducted their experiment relative to variable-rate nitrogen fertilization of spring wheat for five years (2014-2018). Their findings showed no gain in yield as compared to conventional practices. For two out of the five years, wheat yields were slightly higher with variable-rate fertilization, reaching 1.2% in 2015 and 4% in 2016. The year 2015 was characterized by low rainfall, and in 2016, rainfall

exceeded the annual average by 31%. During these years, variable-rate fertilization enabled efficient use of nitrogen fertilizers, as inputs were adjusted to crop conditions. As a result, the study concluded that the benefits of variable-rate nitrogen application are contingent on the climate and explicit in unfavorable conditions for the plant [40].

Fabbri et al., [24] in their results about variable-rate nitrogen application, revealed that with a nitrogen reduction of up to 75%, barley yields were maintained and grain protein levels were higher than with conventional fertilization.

For crops with high added value, fertilizers and soil characteristics have a significant effect on production and profit margins. Applying lime at variable rates adjusts the soil pH to the optimal level for the crop, which stabilizes yields and improves product quality [4].

Bohman et al., [7] research demonstrated that, by respecting the recommended requirements for potatoes, a 15% decrease in nitrogen had no effect on yield. Fernandes et al., [27] used chlorophyll sensors to adjust nitrogen fertilization. And nitrogen inputs were reduced by 38% to 63% without affecting potato yield or tuber quality. Furthermore, the integration of nitrogen management and variable-rate irrigation allowed for the supply of the required quantities of nitrogen and irrigation water, which enhanced the yield characteristics [12].

3.1.3. Precision Irrigation

The numerous technologies tested for precision irrigation have demonstrated their efficiency in managing irrigation water. Evans et al., [23] achieved a water saving of 26% with a site-specific irrigation system. In a semi-arid climate, capacitive sensors have proven their worth in improving irrigation water management in potato fields [21]. Moreover, applying variable-rate irrigation in the onion fields in England, reduced water consumption compared to traditional irrigation methods while maintaining the same level of agricultural production [22]. Similarly, in Italy, precision irrigation has significantly reduced water use in greenhouses growing zucchini without inducing yield losses. Yields were maintained at an average of 30.5 tons/ha by using either precision management or conventional irrigation [13].

However, other studies have revealed increases in yield production, such as in the USA, where corn yields increased by over 1% under precision irrigation [53], while rice yields outperformed traditional irrigation by more than 7% [75].

Also, the yields obtained by precision irrigation of the soybean crop, indicated an average potential increase of 4% to 6.4 % depending on a wet or dry year, respectively [77], in addition to an average potential reduction in water use that exceeds 4%. Additionally, the yields of the soybean crop acquired through precision irrigation showed an average potential increase of 4 % to 6.4% depending on a wet or dry year respectively [77], in addition to an average potential reduction in water use that exceeds 4%. During drought years, precision irrigation can have significant potential for improving irrigation efficiency and yield production.

3.1.4. Site-Specific Pesticide Application

The main effect of site-specific pesticide application technologies can be summed up as a reduction in pesticide quantities, with controlled intervention and preservation of yield quality. According to [16], site-specific fungicide application has limited effect in preventing fungal spread in the soil. Also, the use of a decision support system (DSS) for downy mildew monitoring, has shown the effectiveness of interventions during the potato production cycle [29].

Gonzalez-de-santos et al., [33] conducted tests on a variety of site-specific herbicide treatment devices. And by precise targeting of treatment areas, experiments have revealed a more efficient use of production resources by reducing the amount of herbicides and fuel used compared to conventional applications. Furthermore, the reduction in weed burden could contribute to yield improvement or sustain the level reached by conventional application [33].

Similarly, the site-specific herbicide treatment of field crops (wheat and barley) in Germany decreased the amount of pesticides by reducing the area treated. However, no effect on yield was determined [69]. Similar results were seen in Germany when field crops (barley and wheat) were treated with herbicides at specified sites, which decreased the amount of pesticides used by reducing the area treated. However, no effect on yield was determined [69].

The effect of pest and disease attacks on crop production is probably more notable than an increase in yield following phytosanitary intervention. For this reason, the main objective of site-specific pesticide applications is to maintain yield levels without destroying product quality. Therefore, high-value crops that are susceptible to pathogens require appropriate management practices to sustain commercial yield [55].

In summary, yield is an essential component of a farm's production model. Precision farming technologies make it possible to minimize the environmental impact of agricultural practices while maintaining or improving yield levels when they replace inadequate conventional interventions. As a result, research is unlikely to consider a significant impact of technologies on crop yield but rather to analyze the evolution of economic and environmental parameters without any reduction in production.

3.2. Economic Impact

Farmers mainly seek to achieve economic benefits (reduced input costs, gross margin, break-even point, etc.) by introducing a technology to their farm.

Numerous researchers have long been interested in site-specific management [11, 32], although their findings do not reflect economic and financial potentials. For [31], site-specific management generates additional costs associated with the use of technology. These costs are broken down into four categories:

1) *Information costs*, relate to investment in the instru-

ments and resources required to gather information.

- 2) *Data processing costs*, include software costs, specific resources, and the time required to set up site-specific management programs.
- 3) *Costs of management adaptation*, converting to precision farming entails costs related to modifying and adapting the management system, including equipment purchases.
- 4) *Learning costs*: these relate to the risk of inefficient use of PA technologies during the introduction phase.

In addition, for some kinds of technology, the cost of skilled labor and the cost of expertise are crucial. Consequently, an a priori economic study of the technology introduction is necessary to assess the investment in a precision farming system. Also, Gandorfer and Meyer-Aurich [27], have indicated that a thorough economic evaluation also involves an ex-post analysis.

Indeed, an economic evaluation is not limited to an analysis of the investment in PA, but also to an analysis of the impact. This is why additional studies have examined the effects of implementing the precision farming system using different approaches.

Schneider and Wagner [91] made a comparative analysis, between site-specific nitrogen fertilization based on sensors

and mapping and site-specific fertilization using neural network and decision tree algorithms. Then, according to the partial budgeting method, mapping technique has shown a negative contribution to profit was anticipated to -14 €/ha. The sensor system produced a 16 €/ha economic benefit. The greatest benefit, however, was shown when using neural networks and decision-tree algorithms; this was 46 €/ha more advantageous than conventional management and 26 €/ha more advantageous than using sensor management. As a result, the better the technology's ability to gather the data required to make accurate decisions, the more explicit the economic benefit [11].

On the other hand, other research has examined the impact of site-specific input management using production functions, and it has been concluded that, at the level of its economic optimum, site-specific fertilizer management is characterized by flat gain functions. In other words, slight variations in fertilizer units relative to the optimum result in negligible marginal economic benefits for farmers [65].

At the same time, contemporary advances are pushing the application of precision farming technologies in a wide range of contexts, and several approaches to valuation have been employed (Table 2) to demonstrate the economic benefits.

Table 2. Studies have analyzed precision farming's economic advantages.

Reference	Research methodology	Analysis method	Cultivation	Country
[8]	Survey	Descriptive statistics	Wheat	Brazil
[13]	Experimentation	Life Cycle Cost LCC	Zucchini in a green-house	Italy
[14]	Experimentation	Cost/benefit analysis	Wheat	China
[22]	Experimentation	Cost/benefit analysis	Onion	England
[35]	Experimentation	Cost/benefit analysis	Barley, wheat	Belgium
[43]	Experimentation	Cost/benefit analysis	Barley	Denmark
[47]	Experimentation	Parametric analysis: Revenue, profit, expenses	Apple	Greek
[55]	Experimentation	Monte-Carlo method, Sensitivity analysis	Apple	United States
[56]	Experimentation	Life cycle assessment (LCA)	Barley, rapeseed, Soy-bean, wheat	Australia

Table 2. Continued.

Reference	Research methodology	Analysis method	Cultivation	Country
[60]	Experimentation	Cost/benefit analysis	Maize	Belgium, France
[69]	Experimentation	Partial budgeting	Wheat, barley	Germany
[76]	Survey	Partial budgeting analysis	Wheat, potatoes	Belgium, Germany

Reference	Research methodology	Analysis method	Cultivation	Country
[82]	Experimentation	Regression analysis, parametric analysis: gross margin, NPV (nette presente value), IRR (Internal Rate of return), payback period	Wheat	Spain
[88]	Experimentation	Parametric analysis: Costs, cash-inflow	Corn, cotton, soybean	United State
[89]	Survey	Descriptive statistics	-	United States
[93]	Experimentation	Descriptive statistics	Cotton	United State
[96]	Experimentation	Partial budgeting	Soybean, maize	Brazil

3.2.1. Precision Seeding

The study conducted by [14] evaluated the economic advantages of both seeding techniques; precision seeding and conventional seeding. By opting for precision seeding, the costs of services and of implementing precision technologies have increased the total cost of inputs. However, cost-benefit ratios were 2.11 for precision seeding and 2.27 for precision seeding with laser leveling, an increase of 8.1% and 16.7%, respectively, compared with conventional seeding. Additionally, compared with conventional seeding, the net return for precision seeding increased by 15.5%, or 202 \$/ha, and for precision seeding with laser leveling, it was a surplus of 30%, or 546 \$ / ha. Nonetheless, a subsidy for technologies related to precision farming will help raise the net return even further [14]. In addition, the integration of precision farming technologies into agricultural practices increases income compared with the use of a single technology [14, 51], as they provide precision and control of variability [48].

Corassa et al., [19] chose variable-rate seeding in their experiment to determine the optimal seeding rate for soybeans. The used technique reduces the seed rate by as much as 18% without compromising yield.

In the same context, [88] in their study showed the effectiveness of using Automatic Section Control (ASC) system for planters, avoiding double planting of row crops. However, the time required to recoup the investment in the ASC technology depends on farm size and field conditions.

Munnaf et al., [60] have compared the economic response of uniform seeding rate (URS) with site-specific seeding (SSS) of maize. According to their findings, the gross margin increased from 26.7 to 92.67 €/ha respectively, this benefit being mainly due to the 180% increase in yield from 0.25 to 0.7 Mg/ha.

3.2.2. Variable Rate Fertilization

The use of precision farming technologies, such as prescription maps and sensors, has shown potential savings in crop production inputs of up to 23.9% while also reducing environmental impact [56]. Similarly, Colaço and Bramley, analyzing the studies of using sensors for site-specific nitro-

gen management, revealed nitrogen fertilizer savings ranging from 5% to 45%, with less impact on yield [17].

Guerrero et al., [35] in their experiment conducted on variable rate nitrogen fertilization (VRNF) of cereals, deduced a reduction in applied nitrogen of over 19% with a benefit of up to 19.52 €/ha. In the same way, variable-rate fertilization of apple trees has resulted in fertilizer savings of over 60%, with a consequent reduction in fertilizer costs of up to 7.6% [47].

The application of lime at a variable rate in the experiment conducted by Kuang et al., [43] showed an economic benefit of 2.5 €/ha; however, this benefit was not significant over one year of experimentation, requiring a longer-term study.

Karydas et al., [41] carried out their study on the development and use of a farm management information system (FMIS). Fertilization management using FMIS enabled farmers to increase their plot yields by around 15%. As a result, input costs can be economized by up to 20%.

Soto et al., [76] in their study across five European countries for two types of precision farming technology, reported that the evolution of net income varied with farm size. An increase in net income ranging from -18 to 34 €/ha per year with the use of guidance system machines and from -16 to 411 €/ha per year for variable rate application technologies. Although the PA technologies have allowed for labor and working time reductions, they also come with a price tag for assistance and counseling about the management of these technologies.

Tenreiro et al., [82] analyzing the economics of variable-rate nitrogen application, obtained negative annual differential gross margins for 50% of the examined years (3/6 years) due to the crop*year interaction and exogenous variables like investment support policies. Also, the assessment of the viability of the variable-rate application revealed a correlation between profitability and the minimum cultivated area, which needs to exceed 500 ha annually. Furthermore, the internal rate of return (IRR) is affected by variations in inputs and outputs, as well as by the way the equipment is operated (purchased, leased, or subcontracted) [82].

3.2.3. Precision Irrigation

El Chami et al., [22] have conducted a cost-benefit analysis

study on precision irrigation in an onion production system in England. Comparing precision irrigation with conventional irrigation, the results showed that precision irrigation saved 22.6% more water than conventional irrigation. Consequently, the added value of irrigation water consumed rose from 2.36 €/m³ per conventional irrigation to 3.02 €/m³ per precision irrigation [22]. Despite the precision irrigation system's ability to save water and use irrigation water more efficiently, the investment in this technology surpasses that in conventional irrigation, coming in at 720 €/ha and 766 €/ha, respectively [22]. Positive net benefits have been produced by precision irrigation, although they are on average 0.7% less than those of traditional irrigation [22]. These benefits are positively correlated with the degree of soil variability. Similarly, farmers in Brazil have perceived increased crop productivity, optimal planning of farming interventions, savings on input costs, and positive net benefits. Except that these economic benefits for site-specific applications depend on the rate of field heterogeneity [8].

In the Mediterranean region of Italy, [13] analyzed the impact of precision irrigation by opting for a decision support system (DSS) and an automatic management system connected to sensors in greenhouse zucchini plantations. The result of the economic cost-benefit analysis showed that production costs are mainly affected by the water component. The decision support system and sensor-based irrigation systems produced total costs of 3127 €/ha and 3222 €/ha, respectively, while the farmer's irrigation practices generated a total cost of 3274 €/ha. However, the contribution of the investment costs of the decision support system approach and sensor-based management to production costs is only 16% and 18%, respectively [13].

Furthermore, precision irrigation technologies have advantages in terms of the efficiency of the use of irrigation water. Precision irrigation of potato fields in England has resulted in water savings of approximately 20 mm/year in humid climate zones. However, the benefits of precision irrigation depend on the extent of soil heterogeneity in the field, climatic conditions, the mode of irrigation, and the cost of water [20]. Similarly, Mendes et al., [57] have developed an intelligent variable flow irrigation system for bean fields that has resulted in up to 27% water savings.

3.2.4. Site-Specific Pesticide Application

Yang, 2020 [93] investigated the effect of site-specific pesticide management based on prescription map technology, multispectral imagery, and data processing software. His experiments in South Texas on cotton root rot showed a reduction in fungicide expenses, as targeting infested areas meant that only 57% of the field was treated. Consequently, compared to a uniform treatment, the quantity of fungicide was reduced and its cost was lowered by 43%, saving 2400 \$ [93]. The study made use of cutting-edge precision technologies that have demonstrated their technical effectiveness, including aerial images captured by aircraft and satellite im-

ages, in addition to image processing software and control systems for variable-rate fungicide application. However, the investment in these tools can only be recouped if the area treated is reduced by more than 70% through site-specific management [93].

Compared with conventional application, [55] estimated average pesticide cost reductions of 60 - 67% with variable-rate application. Also, the technical analysis of the technology revealed a 27–32% decrease in overall application time, estimated at 16–26 minutes, as compared to traditional application times. In addition, variable-rate application technologies have contributed to reducing working hours and saving about 28% on fuel [55]. Zanin et al. [96] explored a site-specific approach to pesticide management based on real-time sensors. An economic evaluation of the feasibility of site-specific spraying showed a 56% reduction in application costs compared with uniform spraying, thanks to lower volumes of pesticides applied.

In the same vein, [69] compared conventional farmer control with site-specific pesticide application based on two monitoring approaches: RGB images and drones. The findings demonstrated that fungicide costs were reduced by 38%, or 75 €/ha, and herbicide costs were reduced by 66%, or 111 €/ha, compared with uniform application. Additionally, site-specific applications resulted in extended gross margins 18% to 22% higher than the reference. However, investment in technology generates additional average annual costs of €17/ha, ranging from 21 €/ha to 37 €/ha.

Gusev et al., [37] pointed out in their study that the use of PATs such as satellite vehicle monitoring systems has led to savings in production resources, including a 6.3% reduction in fuel consumption, a 1.1% reduction in seed consumption, a 3.1% reduction in fertiliser consumption and a 3.6% reduction in phytosanitary products. As a result, profitability has increased by 0.78%.

3.2.5. Minimum Application Area

Precision agriculture manages variability; [44] revealed that field heterogeneity generates specific management zones, which creates higher economic benefits compared to a uniform field. The managed area affects the intensity of the impact of PA technologies. For this reason, the concept of minimum area has been brought up in several studies looking at the economic advantages of precision farming technologies.

Rajmis et al., [69] considered the minimum area of application to be the area of grain from which farmers can offset the costs of precision farming technology. They concluded that to save 70% of pesticide costs, the minimum area for drone spraying is 314 ha and an area of 597 ha for site-specific management by sensors. Whereas, areas of 1593 ha and 3024 ha for site-specific applications using drones and sensors, respectively, only enable a 30% reduction in costs.

Tenreiro et al., [82] defined the adoption threshold as the minimum farm area that ensures the economic viability of

variable-rate nitrogen application technology. The analysis showed that an area larger than 567 ha per year planted with wheat would be economically advantageous. The rise in wheat prices and the intervention of support policies mean that this area decreases between 68 and 177 ha/year. Manandhar et al., [55] deduced an amortization period for variable-rate pesticide application technology of 3.8 years for a 4 ha apple orchard and 1.1 years for a 20 ha area.

As a result, both the investment needs and the cost of interventions vary across technologies. Nevertheless, as the minimum surface area increases, economies of scale can be achieved, and the farmer recoups his investment.

In conclusion, the economic benefits of PA are affected by a set of factors that are either endogenous, linked to the characteristics of the field and the costs generated by the technologies [8], or exogenous, which are particularly linked to input price policies, investment policies, etc. However, PA technologies are likely to have a direct or indirect economic impact [3]. Variable-rate application technologies have shown explicit economic benefits due to their ability to help reduce input costs (fertilizers and water) while improving farm profitability [36]. In this regard, surveys conducted by [89] revealed that 33% of adopting farmers appreciated an increase in the profitability of the technologies of at least 5%. Over 65% of these farmers realized profits from variable-rate fertilizer and seed application technologies, and 66% from automatic section control technologies.

3.2.6. Precision Agriculture Technologies for Small Farms

Smallholdings include farms with areas ranging from less than one hectare to 10 hectares [26]. The class of farms with less than 2 hectares constitutes 84% of agricultural farms worldwide, particularly in low-income and lower-middle-income countries [25]. Small farms present difficulties in adopting precision agriculture technologies due to the size of the plots, the high cost of the technology, and the lack of professional and financial support. Given this, proving the financial advantages of PAT for this type of farm is chal-

lenging [59]. The results of several studies have shown that farm size strongly impacts economic results [5-74, 76-88]. Certain classes of farms can even have a negative impact on net income [76].

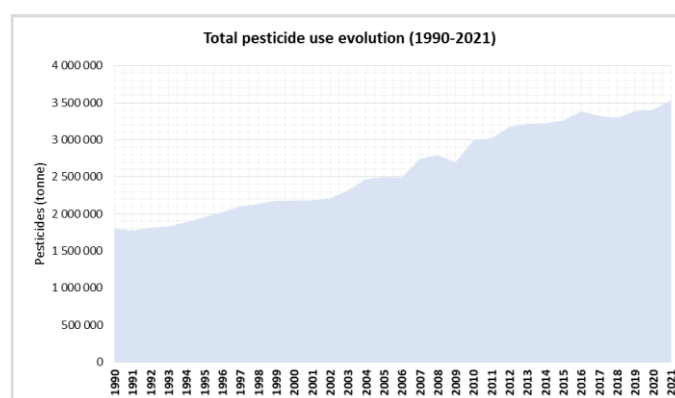
Small farms' revenue and business activities render certain technologies unaffordable, thereby hindering their adoption. Consequently, it is found that some technical categories, particularly in emerging nations, are more advanced than others [59]. These mainly include satellite imagery, mobile applications, and unmanned aerial vehicles, sometimes known as drones [86, 94]. Due to their usefulness in collecting information for managing variability, these technologies are being developed by various collective use modes for small farms (e.g., companies providing services to cooperatives) [78, 86].

Notwithstanding the barriers to smallholder adoption of precision agriculture technologies, their use has potential benefits. PATs increase agricultural labor and energy efficiency and effectiveness [42, 79], and they promote the attractiveness of agriculture to young people in rural areas [42]. Furthermore, PATs demonstrate their environmental utility while optimizing the use of production resources (fertilizers, water, and energy) [2-17, 18-20]. This advantage assists in the sustainability of small farms. Therefore, it is crucial to develop technologies that are appropriate for small farms and their production systems.

3.3. Environmental Impact

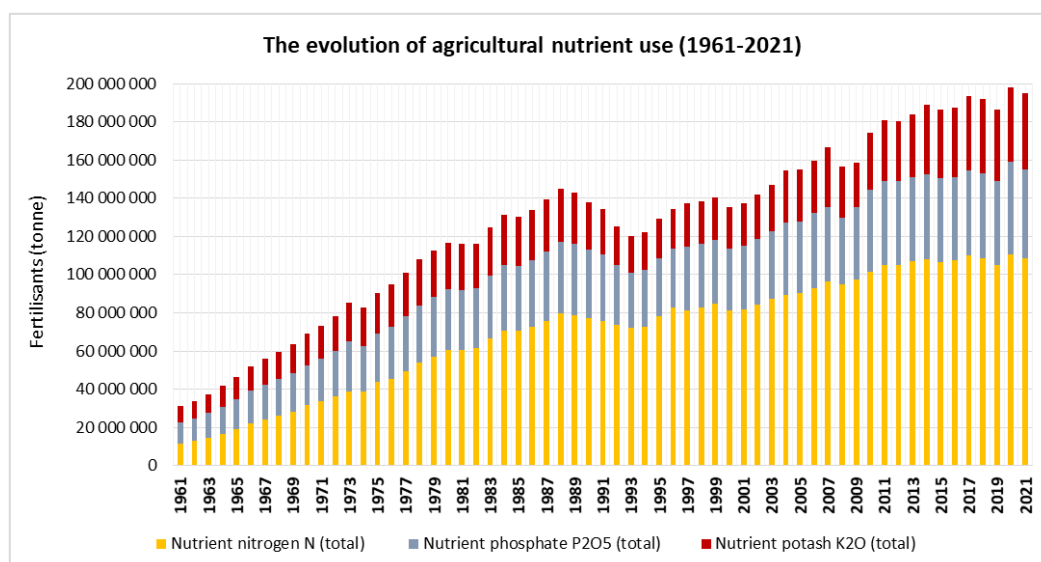
3.3.1. Agriculture and Environment

Agricultural activity interacts strongly with the environment and is intimately related to natural resources. On a global scale, agriculture mobilizes large quantities of fertilizers (N , P_2O_5 and K_2O), increasing from 31 Mt in 1961 to over 195 Mt in 2021 (Figure 3). Similarly, the use of pesticides in agriculture has increased by 97%, from 1.7 Mt in 1990 to 3.5 Mt in 2021 (Figure 2).



Data source: (FAOSTAT, 2024)

Figure 2. Evolution of pesticide use in agriculture.



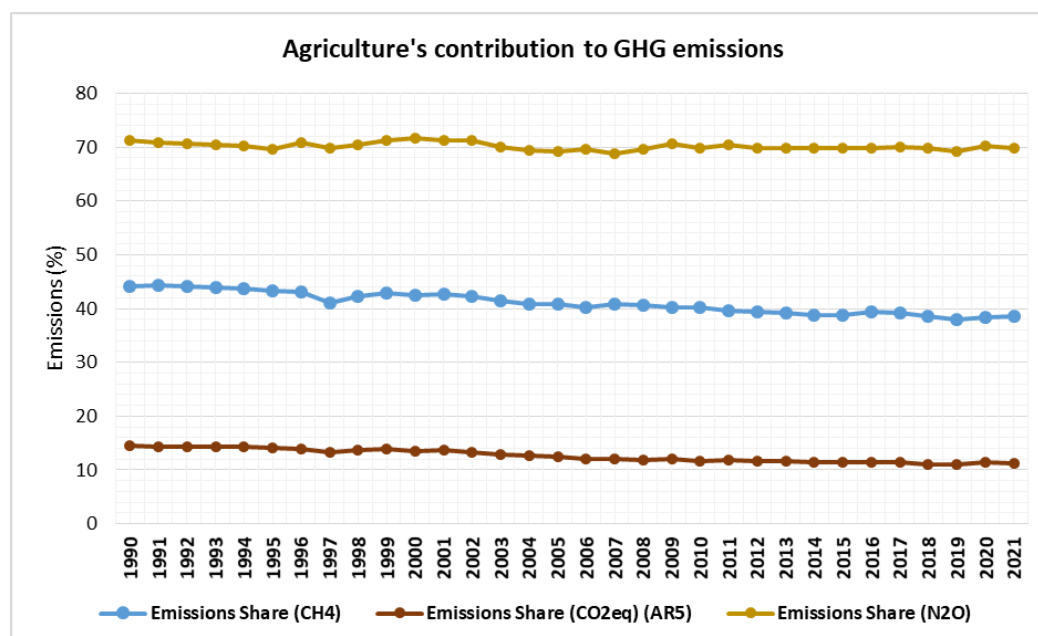
Data source: (FAOSTAT, 2024)

Figure 3. Evolution of fertilizer use in agriculture.

At the same time, 11.2% of global greenhouse gas (GHG) emissions in 2021 will come from agriculture. Agriculture's contribution to greenhouse gas emissions has decreased during the last ten years (Figure 4), thanks to efforts to reduce the environmental impact of agriculture.

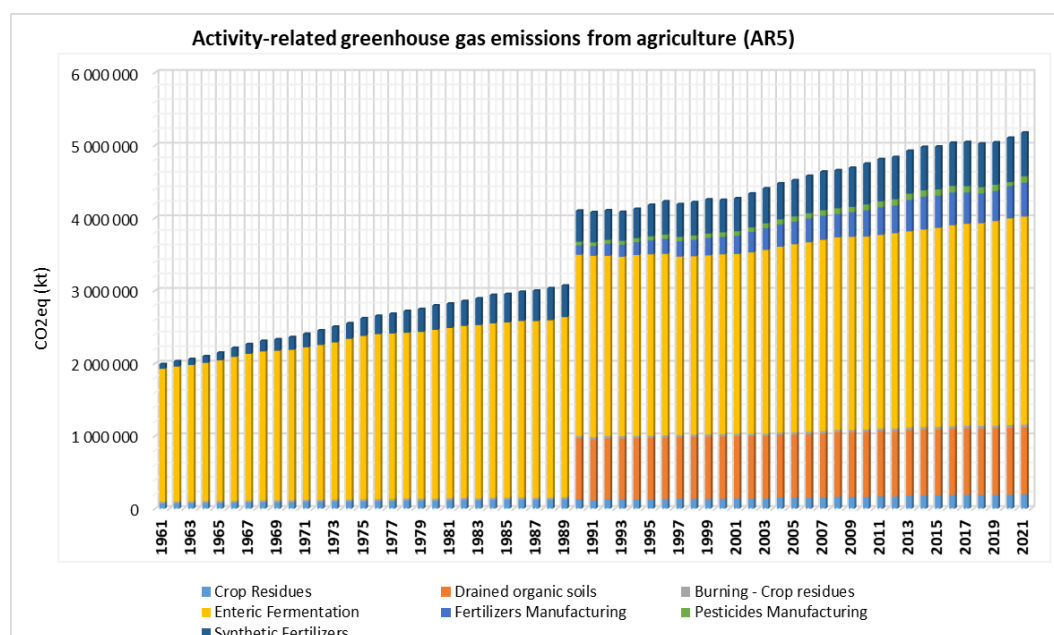
However, the agricultural sector includes activities with higher GHG emissions linked to enteric fermentation, cultivated soils, and fertilization practices (Figure 5). Excessive

fertilization has adverse effects on the environment, with around 20-50% of fertilizers applied being converted into greenhouse gases (GHGs) such as methane, nitrous oxide over fertilization harms the environment since 20 –50% of fertilizers are released as greenhouse gases (GHGs), including carbon dioxide, nitrous oxide, and methane [92]. Furthermore, overuse of pesticides in agriculture poses a risk to biodiversity and contaminates ecosystems [64].



Data source: (FAOSTAT, 2024)

Figure 4. Agriculture activities' contribution to greenhouse gas emissions.



Data source: (FAOSTAT, 2024)

Figure 5. Agriculture activities' contribution to greenhouse gas emissions.

Therefore, agriculture needs more sustainable management practices to face the challenges of food security and the preservation of natural resources. The employment of PA technologies contributes to environmental conservation thanks to the range of advantages offered by their use [3, 24-96].

3.3.2. Precision Tillage and Seeding

Naresh et al., [62] conducted six years of research on sugarcane, assessing the impact of precision leveling on energy balance and greenhouse gas emissions. Precision leveling increased energy productivity by 90.7 GJ/ha compared with conventional levelling, which was 198.6 GJ/ha. Similarly, GHG emissions were reduced from 5249.33 to 944.19 kg CO₂eq/ha/year. In addition, laser leveling has been considered a precision conservation technology that has improved the efficiency of irrigation water use [70, 83].

In the same context, [14] examined the effects of residual nitrogen following wheat harvesting in an environmental assessment of precision seeding technologies. The findings indicate that the concentration of nitrate in the soil decreased by 7.9% at a depth of 0–60 cm, while the concentration of ammonia decreased by more than 25% at the same depth. Nitric and ammoniacal residue nitrogen were decreased by precision seeding, however, these effects were not significant at the 0.05% level. The year-long investigation revealed both environmental and economic advantages. In fact, additional favorable impacts may persist and even strengthen in the coming years [14].

In a similar vein, [29] found that precision seeding significantly reduced ammonia nitrogen by 46% and nitrate nitrogen by 26%. In addition, compared with conventional seeding,

ammonia was considerably reduced by 29% with laser leveling.

Li et al., [46] expanded on the environmental impact analysis by examining how precision seeding methods affect soil nitrogen oxidative bacteria's responses. The use of precision seeding technologies had no significant impact on the quantity of ammonia-oxidizing bacteria (AOB). On the other hand, the multiplication of ammonia-oxidizing archaea (AOA) was activated by the reduction of residual soil nitrogen.

In addition, the integration of controlled traffic farming has proven to have positive environmental effects. This technology has minimized fuel consumption by reducing the number of passes made by farm machinery and the time spent working in the field, in addition to reducing the risk of erosion and soil compaction [80].

3.3.3. Variable Rate Fertilization

Millar et al., [58] considered nitrogen fertilization to be the main factor in N₂O emissions. Similarly, [3] mentioned that 90% of total GHGs come from the nitrification and denitrification processes of nitrogen fertilizers in fields.

A. T. Balafoutis et al., [4] assessed the effects of variable-rate nitrogen application for three seasons on vineyards, and deduced a significant reduction in total GHG emissions of over 25% and GHG emissions from fertilization of 38% to 43% for the two vine varieties studied. Also, [40] were interested in assessing the direct impact of variable application technologies. Their analysis focused on two aspects, the energy review and the estimation of GHG emissions from variable-rate nitrogen application compared with conventional fertilization practices. The experiment conducted between 2014 and 2018 demonstrated that variable-rate nitrogen fertilization tech-

nology enabled an increase in energy efficiency, while reducing the energy requirements of agricultural interventions by 12.3%. It also improves productivity by increasing the quantity of product obtained per unit of energy by 9%, compared with conventional fertilization. With regard to GHG emissions, the results of the environmental analysis indicate that GHG emissions from variable-rate nitrogen fertilization (VRF) were 40.4% and 45.5% from conventional fertilization (CF). CO_2 Emissions were reduced by 9.4%, equivalent to 457.9 ± 32.0 kg CO_2eq ha⁻¹ (VRF) versus 505.5 ± 32.5 kg CO_2eq ha⁻¹ (CF).

However, evaluation of the impact of precision fertilization in the short term has not produced any significant results on greenhouse gas emissions [24]. Other studies have linked the effect of precision technologies with intra- and inter-seasonal climatic variability, as soil moisture, temperature, and microbial activity influence the direct processes of greenhouse gas generation from the soil [15, 24-95].

3.3.4. Precision Irrigation

Precision irrigation is expected to have a positive impact on the environment by conserving water inputs and subsequently lowering pumping energy [3]. Also, another aspect of irrigation control is the control of N_2O emission processes in irrigated areas [85]. The variable-rate irrigation system evaluated by [22] reduced irrigation water consumption by 22.6% and CO_2 emissions by 23% compared with conventional practices.

Canaj et al., [13] conducted a life-cycle analysis of precision irrigation technology to quantify environmental effects. The study demonstrated a reduction in environmental risks from 0.03% to 62%. A 12% reduction in the health burden, 11% in resource deterioration, and 13% in the ecological system's quality degradation. Furthermore, the results revealed an energy savings of 340 kWh/ha due to irrigation water savings of 38.8%, without affecting yield. Consequently, precision irrigation technologies have contributed to an overall reduction in environmental impact of 13% per ton of zucchini [13].

3.3.5. Site-Specific Application of Pesticides

Site-specific spraying is a sustainable farm management approach that reduces the treatment frequency indicator (TFI) on the plot while reducing the area treated [16]. The site-specific pesticide application generates positive effects for the ecosystem, and helps restore ecological balance since inputs are targeted and made without destroying fauna and refuges in non-infested areas [87].

SØnderskov et al., [71] evaluated a decision support system (DSS) for weed control. Herbicide use has decreased by almost 60% in Denmark as a result of the implementation of DSS for barley field management (with a TFI dropping from 1.28 to 0.55).

Gonzalez-de-santos et al., [33], considered precise pesticide management as an approach to improving the quality of

agricultural products, and preserving the health and safety of living beings. As such, they have developed a precision herbicide application system. The integration of new precision farming technologies (GNSS, maps, algorithms, robots, etc.) has enabled the design of effective intervention systems. The findings demonstrated that applying precision agricultural technologies to pesticide treatment reduces herbicide use by 75%, thereby reducing risks to health and the environment.

Ultimately, the various precision agriculture technologies have the potential to reduce the impact of agricultural interventions on the environment either directly or indirectly [3]. The first effect revealed was a reduction in the quantities of chemical inputs relating to pesticides and fertilizers. Also, limiting the overexploitation of energy and water resources is a fundamental advantage that ensures the sustainability of production systems. Still, in-depth studies over long time periods are needed to produce consistent outcomes in terms of reducing greenhouse gas emissions and enhancing the quality of soil and groundwater.

4. Discussion

4.1. Impact Assessment

This literature review highlights the results of research examining the impact of precision farming technologies. By analyzing the results of these studies, we have been able to outline the impact of the use of precision technologies in terms of three major aspects: agronomic, economic and environmental, as shown in the figure 6. And generally the effects have been positive, but to different extents.

The agronomic impact consists in improving the production process while increasing yield or maintaining it at the same level as with conventional application [12-14, 48-82]. However, the results may differ from one crop to another [83] and according to the type of technology adopted.

The economic benefits reside mainly in the reduction in the cost of agricultural applications following the reduction in the quantities of water used for irrigation [57], pesticides [69], fertilizers [47] and energy consumption [40]. However, economic gain depends on a number of external factors linked to the effects of climate and market conditions (raw material prices, selling prices, etc.) and other factors internal to the farm: degree of heterogeneity of the soil [8] and the minimum area of application [69, 82], and type of technology used, depending on the agricultural intervention (irrigation, fertilization or phytosanitary treatment).

Nonetheless, the investment cost for certain types of technology outweighs the benefits resulting from their use [22]. This can be seen in the fact that certain agricultural interventions require the mobilization of a range of integrated techniques, or the cost of the technology itself is high.

The environmental benefits of precision technologies are well documented in the results of some previous experiments. The reduction in greenhouse gas emissions is a notable result

[3, 24], as a result of the reduction in the intensity of agricultural machinery use and energy consumption.

Improved soil quality is another potential result, through

improved microbial activity following the reduction in chemical inputs.

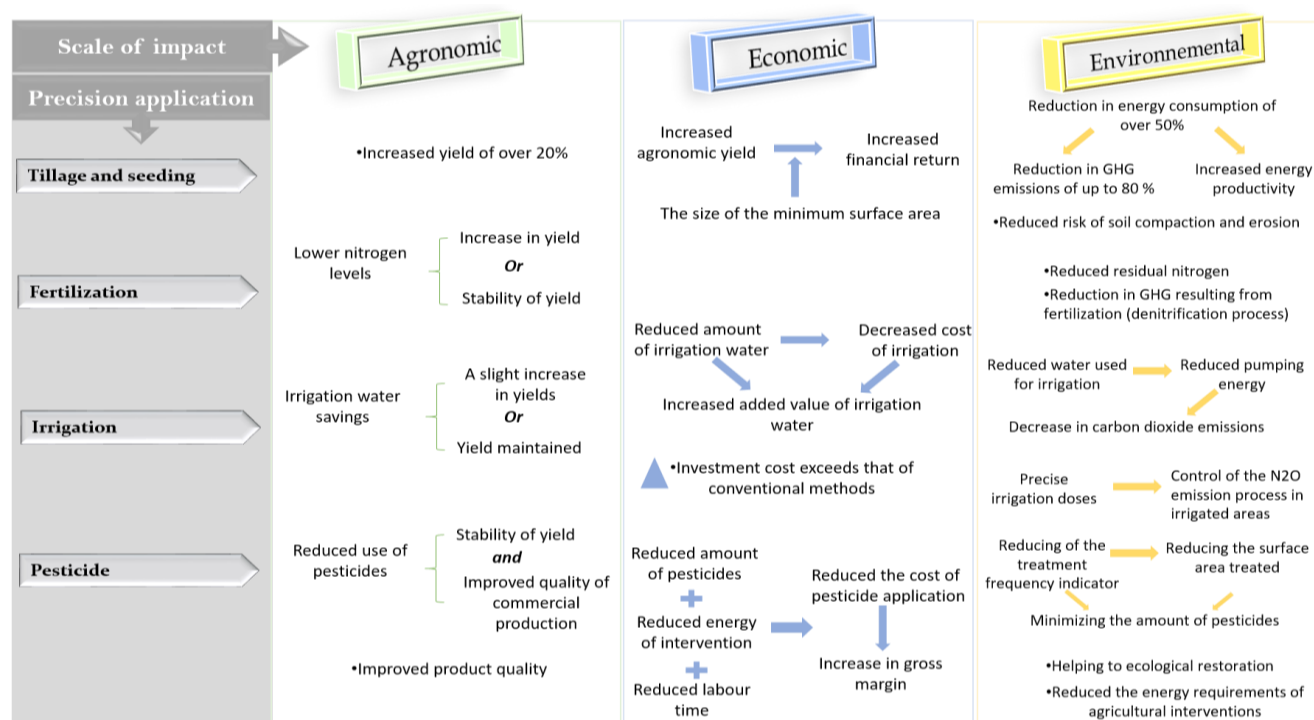


Figure 6. Synthesis of the effects of the use of precision farming technologies on agronomic, economic and the environmental aspects.

Another aspect that will be influenced by the use of precision farming technologies at farm is the social component. The introduction of certain types of technology requires farmers to have a certain level of education for adoption, and or qualified manpower for the handling and monitoring of farm operations [63]. It will therefore be useful to study this aspect by analyzing the impact of the adoption of precision farming technologies on employability and labor costs.

4.2. Analysis Method

Precision farming technologies are used to realize one or more agricultural interventions, and impact analysis extends throughout the production process.

The works examined have opted for different methods of analysis (Figure 7) based mainly on experimentation [82, 22-13]. The life cycle cost method [13, 56] and cost-benefit analysis [14, 22-60, 43-35] can be allows for a transversal analysis from upstream to downstream of production process

for the three aspects (agronomic, economic and environmental) without reaching the social aspect. Partial budgeting used by [96, 69, 76] and Monte Carlo methods [55] were applied to the economic study of precision farming technologies. Descriptive analysis and regression are methods used to analyse agronomic, economic and environmental parameters [82, 88-47].

The strength of each method depends on its ability to analyse several aspects on a large scale and the possibility of extracting trends from the results. The aim of analysing the impact of precision farming technologies on the farm system could be not only to encourage farmers to adopt the technologies [45], but also to analyse the technico-economic efficiency of the use of these technologies [55], to assess the sustainability of production systems [45], and the adjustment of technologies to farm conditions. As a result, studying the impact of precision farming opens up a number of avenues for future research and in-depth studies from different perspectives and on a multitude of scales.

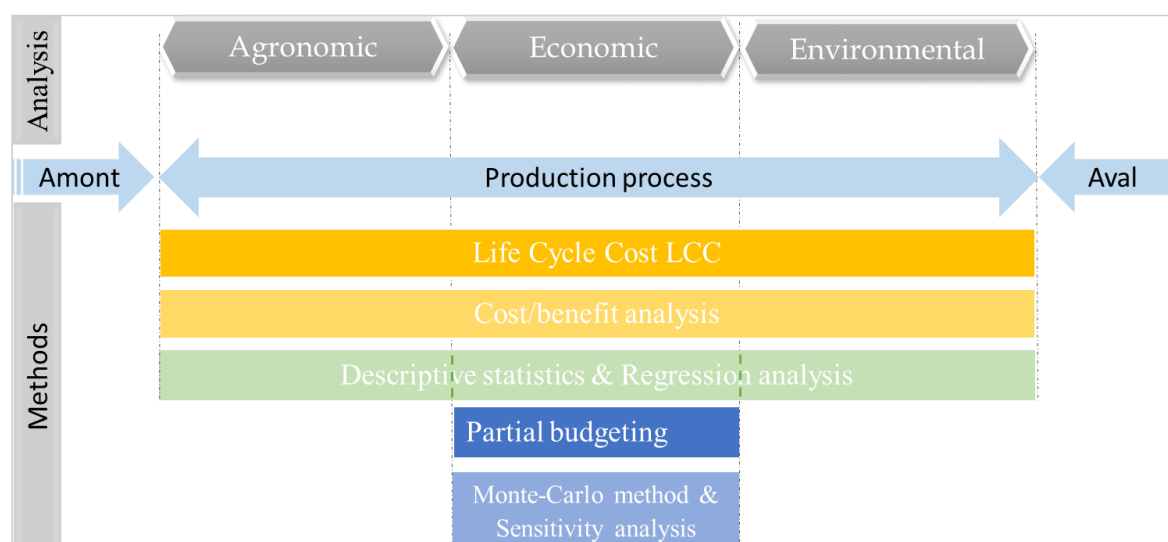


Figure 7. Analysis methods used in the research reviewed.

5. Conclusions and Recommendations

Our work consisted in analysing the impact of the use of precision farming technologies by studying some recent research cases. Then we classified these impacts according to three aspects. The findings demonstrate that precision farming technologies have proven their environmental, economic and agronomic effectiveness.

Based on the results obtained from the works studied, we are recommending four guidelines for future research, and which will also serve to promote the development of precision agriculture:

Determining the balance between the costs and benefits of introducing the technology,

The economic benefits have been shown to depend on a number factors, precisely the type and level of technology used, the size of the farm, and the crop, in addition to the country's economic context, hence the need to multiply research studies in order to bring out a consistent trend in the results. Both small- and large-scale farmers therefore need to incorporate specific technologies into their processes, with a view to optimising their production process.

Analysing the social impact of the use of precision farming technologies

In the age of digitization, precision farming depends on technologies that require a certain level of staff qualification and others that will probably make farms relatively autonomous. Therefore, evaluating the employment and farm economic effects of these technologies is crucial to establishing the socio-economic trends and prospects for this innovative production approach. Also, another social aspect is how these technologies will be adapted to farmers whose level of education does not allow them to handle these advances.

Extend the range of studies for crop groups (e.g. cereals,

market gardening, arboriculture, etc.) and opting for integrated analysis methods

Methods that enable the impact of precision farming technologies to be analysed on a multi-scales can indicate the production systems for which conversion to precision farming is most sustainable. They can also indicate which crops are most profitable with the use of these technologies.

Extending impact studies to the entire farm sector

It would be crucial to explore how precision farming technologies will contribute to making the farming sector competitive and attractive to new investments.

6. Highlights

- 1) Precision pest management and precision irrigation are a sustainable practice.
- 2) Adoption of precision farming reduces the environmental risks.
- 3) Investing in precision farming technologies generates additional costs.
- 4) The minimum application area is important to ascertain economic break-even point.
- 5) Social impact of precision agriculture is a scientific avenue to be explored.

Abbreviations

AOA	Ammonia-Oxidizing Archaea
AOB	Ammonia-Oxidizing Bacteria
ASC	Automatic Section Control
CF	Conventional Fertilization
DSS	Decision Support System
FMIS	Farm Management Information
GHG	Greenhouse Gas
GNSS	Global Navigation Satellite System

IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
NPV	Net Present Value
PA	Precision Agriculture
PAT	Precision Agriculture Technology
RGB	Red, Green, and Blue
SSCM	Site-Specific Crop Management
SSM	Site-Specific Management
SSS	Site-Specific Seeding
TFI	Treatment Frequency Indicator
URS	Uniform Seeding Rate
VRF	Variable Rate Fertilization
VRNF	Variable Rate Nitrogen Fertilization

Author Contributions

Hayat Idier: Formal Analysis, Investigation, Writing – original draft

Mohammed Dehhaoui: Supervision, Validation

Nassreddine Maatala: Conceptualization, Writing – review & editing

Kenza Ait El Kadi: Conceptualization, Writing – review & editing

Conflicts of Interest

The authors declare no conflict of interest.

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