




Review

A Systematic Review of Opportunities and Limitations of Innovative Practices in Sustainable Agriculture

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Abstract: A transformation is needed in agricultural production to satisfy the growing population-based increased food demands and overcome food safety challenges while supporting human health and the preservation of natural resources. Improving sustainable agricultural practices is essential for developing a long-term and resilient economy. This systematic review with meta-analyses aims to overview sustainable agriculture's progress, trends, and future opportunities, focusing primarily on integrating novel technologies into recently prevailing agricultural operations. As a basis, an extensive literature search was conducted, identifying nearly 45,000 records related closely to various dimensions of sustainable agriculture. Out of these, based on a thorough selection process, 291 were included in further evaluations. The temporal distribution and content analyses indicated an improvement in the number of papers and the spectrum of addressed agricultural aspects. The analysis of the publications revealed that most traditional farming practices focus on mass food production and cannot deal with further interrelated sustainability challenges. On the other hand, sustainable agricultural practices consider sustainability's environmental, economic, and social aspects, thereby preserving environmental health and supporting economic viability and social well-being. The integrative assessment in this study suggests that adopting novel, innovative practices can achieve the most significant progress toward agricultural sustainability. At the same time, a broad range of limitations and challenges are listed, which widely hinder the penetration of sustainability initiatives. To eliminate these barriers, consistent policy regulations are required, targeting specific agricultural problems, alongside a complex, education-based support system, further boosting initiatives related to the green transition in agriculture.

Keywords: green transition; agricultural sustainability; agricultural innovation; agro-economy; food production



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1. Introduction

Agricultural activities have a significant impact on the condition of the environment and natural resources through various mechanisms. The most environmentally adverse

agricultural practices include excessive use of chemical fertilizers and pesticides and monocultural mass production, leading to soil degradation, water pollution, and deterioration of organisms [1–5]. Intensive animal husbandry and synthetic fertilizers contribute significantly to the emission of greenhouse gases such as methane, dinitrogen oxide, and carbon dioxide [6,7]. In some areas, the inappropriate disposal of plant residues or the burning of the remains instead of recycling results in extensive greenhouse gas emissions [8]. Using fertilizers and pesticides leads to the eutrophication of lakes, fostering damage to aquatic ecosystems [9]. In addition, soil's physical and agrochemical degradation, including the loss of humus and essential nutrients, is a major environmental burden, especially in regions where acidification of soil or radionuclide (e.g., ^{210}Pb , ^{226}Ra , ^{90}Sr) pollution are causes for concern [10,11]. These suggest that land use faces several challenges in terms of agricultural utilization.

The United Nations (UN) estimates that the global population could increase to 8.6 billion by 2030 [12]. This also means that the agricultural food industry needs to intensify its production. All this is executed with a focus on the fact that existing agricultural areas should not be further increased based on the recent intensity of their management [13–15]. In addition, a reduction in global biological diversity significantly hinders the involvement of new food sources (e.g., seaweed or plant-based alternatives to animal-derived products) and adversely affects food quality and nutrient content [16,17], putting pressure on agricultural systems. With eco-efficient agricultural operations, however, some adverse trends can be counteracted. Binding greenhouse gases in soil and plants, reducing biodiversity loss through new species with elevated resilience, changing nutritional habits through the diversification of diet, and using modern soil cultivation practices to reduce soil depletion and flood risk are all among potential solutions [18,19].

Based on the above, this paper seeks to introduce the development of sustainable agriculture and its practices in the last ten years by conducting meta-analyses of the available literature. Here, the most decisive farming technologies are assessed, focusing on innovations and their adoption in actual practice. Therefore, the implementation conditions of these innovations and their influence on production and the environment are also evaluated. Additionally, the major factors that hinder the spread of these sustainable practices are underlined, thereby determining the areas where there is space for further improvement.

1.1. The Concept of Sustainable Agriculture and Sustainable Agricultural Practices

The Food Agricultural Organization (FAO) defines the concept of sustainable agriculture as follows: “the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations” [20]. As a prelude, the formation of sustainable agriculture frameworks resulted from a long-term evolution lasting several decades. In the early 1980s, many American and European farmers recognized that their operations could hardly be maintained due to financial and environmental constraints; therefore, an alternative approach was required [21]. In this initial period, the proposal widely divided the scientific community, and its progress did not get the boost it deserved. By the late 1980s, however, the deterioration of soil and water bodies, the accumulation of toxic substances, and related health issues became highly evident and perceptible for society, researchers, and also legal bodies, which facilitated the wider acceptance and actual manifestation of sustainable agricultural interventions [22–24]. Since then, the concept has been continuously evolving with consistent debate, with multiple perspectives reflecting the preferences of stakeholders or authors. The approach of a sustainable farming system suggests that agriculture contributes to general well-being by providing sufficient food and other goods and services in an economically efficient,

socially responsible, and profitable manner while also improving the quality of the environment [25]. Some authors emphasize that sustainable agriculture should be assessed from a holistic farming aspect that aims to meet the needs of current and future generations by ensuring profitability, environmental health, and social and economic equity [26].

As a closely related subject, sustainable agricultural practices are tools and measures that support the reform of the whole agrarian sector along complex environmental-social-economic demands. These rely on previously developed methods with recent technological advances (e.g., low/no-emission machinery) and novel solutions (e.g., artificial intelligence) that aim to increase agricultural standards and productivity and subordinate total agricultural production to sustainability purposes [27]. From an ecological perspective, sustainable practices aim to maintain and improve the quality of the environment, even under the pressure of extensive farming operations. From an economic point of view, sustainable agricultural practices must ensure the long-term maintenance of farming activities, maintain economic resistance to market fluctuations, and meet the changing needs of consumers. These practices include the social aspect of sustainability by promoting the life quality of farmers, agricultural workers, and wider society, and improving food safety and healthy nutritional opportunities [28]. Additionally, sustainable agriculture based on innovative practices can contribute to achieving the Sustainable Development Goals (SDGs) of the United Nations, especially no poverty (SDG 1), zero hunger (SDG 2), decent work and economic growth (SDG 8), reduced inequalities (SDG 10), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14), and life on land (SDG 15) [29]. Thus, according to unanimous opinion, sustainable agriculture and its supporting practices are critical elements of future development.

1.2. New Research Directions Related to Sustainable Agricultural Practices

Considering the core focus areas, ecological intensification is a key strategy in sustainable agriculture, advocating for replacing anthropogenic inputs with environmentally friendly and sustainable alternatives. As suggested by scientific representatives, this approach underscores the need for the sustainable use of natural resources such as soil, water, nutrients, and other biotic and abiotic factors to achieve high performance and efficiency of agricultural yields. With similar goals, sustainable intensification has a broader definition range, including a wide variety of models and novel technologies that serve eco-efficient operations [30–32]. In addition to ecological intensification, genetic and socio-economic intensification are also evaluated in the literature. Genetic intensification, for instance, focuses on enhancing the genetic structure of plants to improve yield, resist pests and illnesses, tolerate harsh weather conditions, and enhance nutritional quality [33–36]. Socio-economic intensification, on the other hand, evaluates economic and social factors that can help improve farming, including the establishment of better markets for farmers. Further, it promotes the creation of training and education platforms related to modern technologies, the appropriate governmental regulatory and support policy systems, and the building of communities [37–40].

Another direction is climate-smart agriculture, which is considered the manifestation of intelligent agriculture [41]. The FAO defined climate-smart agriculture as “*an approach for transforming and reorienting agricultural production systems and food value chains so that they support sustainable development and can ensure food security under climate change.*” [42]. Researchers are looking for practices that use the latest technological achievements and aim to reduce greenhouse gas emissions and water use while helping farmers adapt to and relieve the effects of climate change. Thus, these methods (e.g., cover cropping and nutrient recycling) promote the resistance of the sector to changing environmental conditions [43–48]. General resistance of the sector is a highly important issue, while

current agronomic practices reportedly face three interrelated challenges: the spread of pathogens in soil-human microbial loops, antibiotic-resistant genes in agroecosystems, and the impact of chemical pesticides on human and environmental health [49].

Among the trends in sustainable agriculture, research in agroecology stands out for its holistic approach. Agroecology, which integrates ecological principles with agricultural practices, aims to create sustainable and resilient food systems. This trend emphasizes the interconnectedness of plants, animals, humans, and the environment to balance food security and promote biodiversity and environmental health [50,51]. According to the most common views, agroecology deals with the exploration of the underlying causes of unsustainable agricultural systems but also links environmental security, production, consumption, and social innovation by promoting strong social movements, participatory frameworks, and alternative markets [52].

2. Materials and Methods

A systematic approach was used to review the relevant recent literature (published since 2015) for a thorough and accurate overview. As a first step, the database of Web of Science was scanned to find relevant publications using the topic search term “sustainable agriculture”. Further, the databases of Google Scholar, PubMed, Scopus, and ResearchGate were also inspected using the aforementioned keyword. The resulted publications have been cumulated and listed with their bibliometric data, keywords, and abstract. According to the titles of listed publications, a pre-filtering of duplications was performed in Microsoft Excel. A summary of the literature selection process can be seen in Figure 1.

The first phase of this identification procedure resulted in more than 42,600 hits. Additionally, the reference list of 1000 randomly selected papers (from the 42,646 hits) was also revised to reveal additional publications outside of the studied databases but within the scope of this analysis. This complementary search yielded 1983 publications. After that, duplications were filtered out using the Bramer methodology [53]. Following the identification process, the key search terms “sustainable agricultural practice”, “agricultural technology”, and “sustainable management” were designated by the authors of this paper. These keywords were selected and used with the aim of including general aspects (with the keyword “sustainable agricultural practice”) and more specific ones (“technology” and “management”) simultaneously, thereby representing some of the most studied directions in sustainable agriculture in the literature. To combine or exclude keywords, “AND” and “OR” Boole operators were used, according to Booth and his co-author [54]. The refinement targeted papers in English, published between 1 January 2015 and 30 June 2023. However, to obtain a more comprehensive overview, discussions were also crafted based on publications from the year 2024. Studies were subject to specific criteria: we only assessed documents that were research papers, review articles, and book chapters focusing on sustainable agricultural practices. With these prerequisites, we selected 5800 sources for the subsequent analysis phase. In the following selection process, a two-step filtration approach was applied. First, relevant studies (research papers, review articles, book chapters) were identified by reviewing titles and abstracts, and it was then determined based on a complete text overview whether to involve the given source of literature in further research phases [55]. In more than 4100 cases, abstracts of papers referred to sustainable agriculture; however, the text scanning revealed no actual inclusion. The topic remained at the level of mention without in-depth assessment or critical scientific approach to any extent. In this stage, the number of selected studies was reduced to 1227. We made a template for the selected studies according to Clarke and Braun’s guidelines that allowed systematic data recovery from studies. Due to this, we recorded details such as the scientific field of study. Here, we excluded scientific fields outside of the agricultural economy, food

economy, and sustainability sciences based on the year of publication, abstract, methods, main findings, and the exclusion of sustainable farming practices [56]. After excluding papers with the features above, 291 studies remained compliant. For these publications, we also considered the yearly progress of research and, where possible, highlighted the literature-based development of each concept. From the last ten years, such studies and their main research focuses were highlighted, which, based on the number of papers with similar topics from specific years and according to a content analysis, covered and introduced the presented agricultural issues the most extensively (see Table 1).

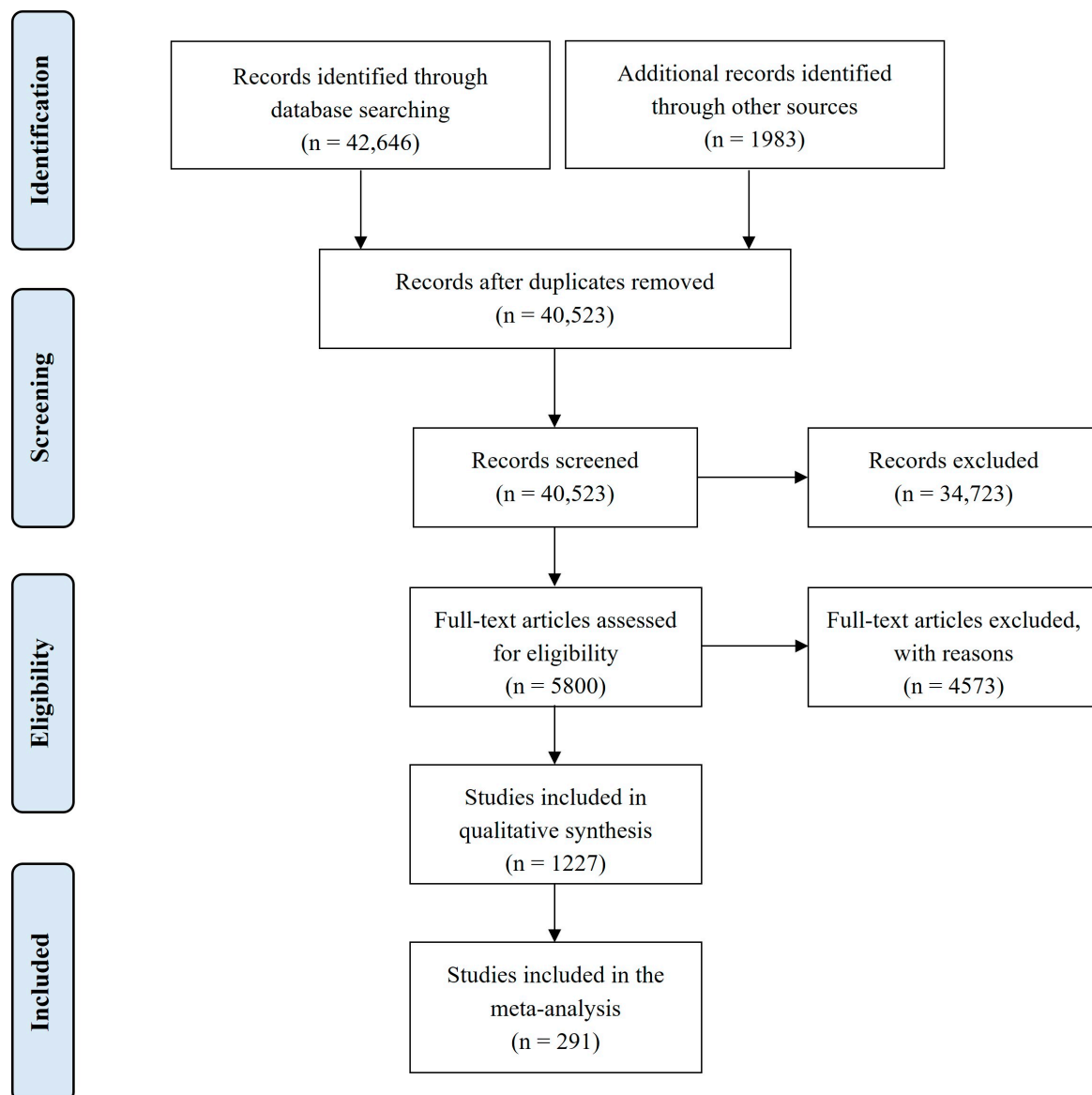


Figure 1. PRISMA flow diagram demonstrating the selection process within the analysis (i.e., the number of studies identified, excluded, and included).

Table 1. Some of the most significant practices in sustainable agriculture according to the time series of the literature.

Sustainable Agricultural Practices	Geographical Scope Discussed in the Paper	Source
Seed treatment methods for sustainable agriculture: (a) physical seed treatment, (b) hot water treatment, (c) dry heat treatment, (d) aerated heat treatment, (e) radiation treatment, (f) chemical and biological treatment, (g) seed soak in aqueous fungicides, (h) use of antibiotics, (i) seed soak in inorganic chemicals, (j) seed dressing, (k) seed coating, (l) seed pelleting, (m) permeability, (n) fluid drilling, (o) seed priming, (p) microorganisms, (q) future bioprotectants.	Global (general)	[57]
Strategies for the sustainable agricultural framework: (a) adaptive management, (b) cooperation, (c) ecology-based strategy, (d) economics-based strategy, (e) holistic and complex systems thinking, (f) knowledge and science, (g) subsidiarity.	Global (general)	[58]
Cultivation patterns: (a) crop diversification, (b) intercropping of maize with food crops.	South Africa (Kwazulu-Natal)	[59]
Conservation agriculture: (a) direct sowing, (b) rip line seeding, (c) planting basins.	Zimbabwe	[60]
Practices to increase maize yield: (a) establishment of furrows against soil erosion and for increased water retention, (b) cultivation of species with specific root structure against soil erosion, (c) rainwater retention, (d) application of inorganic fertilizers, (e) seasonal crop rotation, (f) application of green fertilizers, (g) mulching for better soil health, (h) application of lime for soil pH optimization.	Southern Africa (Chinyanja Triangle)	[61]
Soil protection: (a) organic manuring, (b) precision manuring, (c) integrated manuring, (d) green manuring.	Finland	[62]

Table 1. Cont.

Sustainable Agricultural Practices	Geographical Scope Discussed in the Paper	Source
Automation of conservation agriculture: (a) seeders and planters, (b) power sources, (c) weed control and cover crop management.	Africa, Asia	[63]
(a) agroforestry, (b) intercropping, (c) overcrops.	Zambia	[64]
Role of nanotechnology: (a) nanoencapsulation, (b) nanopesticides, nanoherbicides, (c) nanobiofertilizers, (d) nanoclay, (e) nano-assisted release of genetic material for quality upgrading.	India	[65]
Stakeholders' evaluation on climate-smart agriculture: (a) dugwell excavation, (b) livestock insurance, (c) tubewell, (d) climate-smart housing for livestock, (e) crop insurance, (f) drip irrigation, (g) sprinkler irrigation, (h) check dams, (i) vermicompost, (j) farmyard manure.	India (Maharashtra)	[66]
Resource management: (a) integrated plant protection, (b) integrated nutrient management, (c) soil protection, (d) water management.	Global (general)	[18]
(a) conservation agriculture (CA), (b) climate-resilient agriculture (CRA), (c) climate-smart agriculture (CSA), (d) sustainable agriculture (SA), (e) sustainable agricultural intensification (SAI), (f) sustainable agricultural extensification (SAE).	Global (general)	[67]
(a) agroecology, (b) nature-inclusive agriculture, (c) permaculture, (d) conservation agriculture, (e) regenerative agriculture, (f) carbon farming, (g) low external input agriculture, (h) organic farming, (i) high nature value farming, (j) climate-smart agriculture, (k) ecological intensification, (l) circular agriculture, (m) biodynamic agriculture, (n) sustainable intensification.	Global (general)	[68]
(a) automation of various practices (e.g., irrigation, tillage, harvesting, yield maximization), (b) use of resistant seeds, (c) modern irrigation techniques (e.g., sprinklers, drip irrigation), (d) use of renewable resources, (e) maintaining healthy soil conditions by supplementing essential nutrients, water, and oxygen.	Global (general)	[69]

Table 1. Cont.

Sustainable Agricultural Practices	Geographical Scope Discussed in the Paper	Source
(a) farm management plan, (b) farming cooperation, (c) sustainable crop rotation plan, (d) soil management, (e) crop nutrient management and organic-based fertilizers, (f) crop protection management, (g) management plan for efficient energy use, (h) farm waste management, (i) use of renewable energy, (j) energy production from biomass and liquid manure, (k) water conservation and management, (l) irrigation evaluation and monitoring, (m) reduction in CO ₂ emissions from machinery and fuel use, (n) reduction in methane emissions from livestock, (o) maintenance and calibration of spraying equipment, (p) use of catch crops, (q) integrated pest management, (r) reuse of agricultural residues, (s) precision agriculture.	Europe, Asia	[70]
(a) conservation agriculture, (b) crop diversification, (c) organic farming, (d) agroforestry.	Europe, North Africa	[71]
(a) conservation agriculture, (b) good agricultural practices (GAP), (c) organic farming, (d) sustainable intensification, (e) permaculture.	Global (general)	[72]
(a) organic farming, (b) conservation agriculture, (c) precision agriculture, (d) agroecology.	Global (general)	[73]
(a) genetic intensification, improvement of crop yields, resistance to pests and illnesses, tolerance to abiotic stress, improving the nutritional quality of food, (b) use of precision breeding with genetic and genomic devices, (c) ecological intensification and increased diversification, farming, cultivation systems, resource efficiency, integrated water and nutrient management, (d) socio-economic benefits.	West Africa	[74]
(a) artificial intelligence, (b) machine learning.	Global (general)	[75]
RNAi-based biopesticides and strategies, including genomics, transcriptomics, metabolomics, and bioinformatics.	Global (general)	[76]
(a) climate-intelligent agriculture, (b) organic farming, (c) biodynamic agriculture, (d) conservation intensification, (e) regenerative agriculture.	Global (general)	[47]
artificial intelligence-based nanotechnology.	Global (general)	[8]

Table 1. Cont.

Sustainable Agricultural Practices	Geographical Scope Discussed in the Paper	Source
(a) precision agriculture, (b) organic farming, (c) agroforestry, (d) aquaponics and hydroponics, (e) biotechnology, (f) AI and BigData, (g) drones and satellite imagery, (h) conservation agriculture.	Global (general)	[77]
(a) crop rotation, (b) cover cropping, (c) conservation tillage, (d) organic farming, (e) integrated pest management, (f) agroforestry, (g) precision agriculture.	Global (general)	[78]
Main focuses of agriculture in the next few years: (a) organic farming, (b) climate-smart agriculture, (c) integrated farming, (d) best practices in management.	Southeast Asia	[79]
The role of artificial intelligence in: (a) production efficiency, (b) yield quantity and quality, (c) food production.	Global (general)	[80]

The selected 291 publications were involved in a meta-analysis; we determined the general topic trends by combining data from the studies. The use of meta-analysis provides an overview of the research topic of sustainable agricultural practices, allowing researchers, farmers, decision-makers, and other stakeholders to draw more clear conclusions about the effectiveness of each agrarian practice. In addition, this method increases the reliability of the findings of our study, as it is based on a higher amount of data, which reduces the possible variability, shortcomings, and methodological differences in investigations in certain studies [81].

However, it is worth noting that due to the very high number of involved studies, the publication list consists of papers of highly varied quality, which is a factor to consider when determining the explanatory power of the related statements. For instance, information disclosed in titles and abstracts sometimes does not entirely cover the main text's subject. Further potential limitations can emerge from the publication bias caused by not incorporating smaller studies (e.g., by assessing a reference list of only 1000 publications from the initial search). Additionally, the high heterogeneity arising from the experimental setup (e.g., location and statistical methods) may also influence the outcome of this analysis [82]. At the same time, in this study, these potential shortcomings are considerably counterweighted by the in-depth keyword search and the complementary scan for further research items in the reference list of papers. Along with this, a solid basis was established for the core conclusions in this paper by highlighting the issues represented most frequently and underlining similar methodology proposals across studies.

3. Results and Discussion

3.1. Scientometric Information on the Relevant Literature

In the preliminary analysis of the 291 publications, the temporal change in the relevant studies was evaluated. The result of the 8-year-long overview is presented in Figure 2.

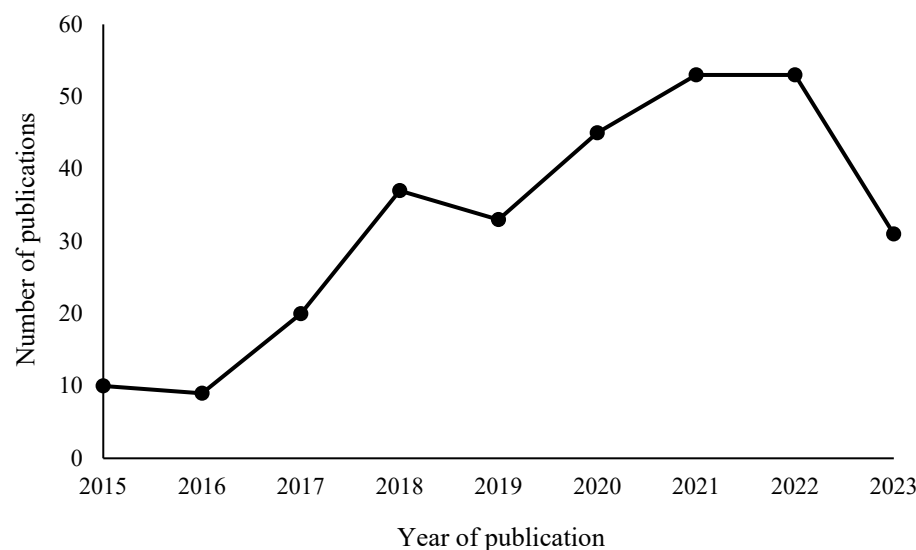


Figure 2. Change in the number of publications related to sustainable agricultural practices between 2015 and 2023.

After the initial low number of papers published in 2015 and 2016, a dynamic increase started in 2017. The publication intensity on the topic reached the highest numbers in 2021 and 2022, with 53 papers in both years. The result for 2023 should be interpreted considering the specific methodology of this paper: the latest studies involved were published in June 2023. During the first six months of the year, 31 papers were published, projecting a continuation of the previous years' ascending trend.

It was also assessed as to which leading journals featured the most publications. The related report for the 2015–2023 period is presented in Figure 3.

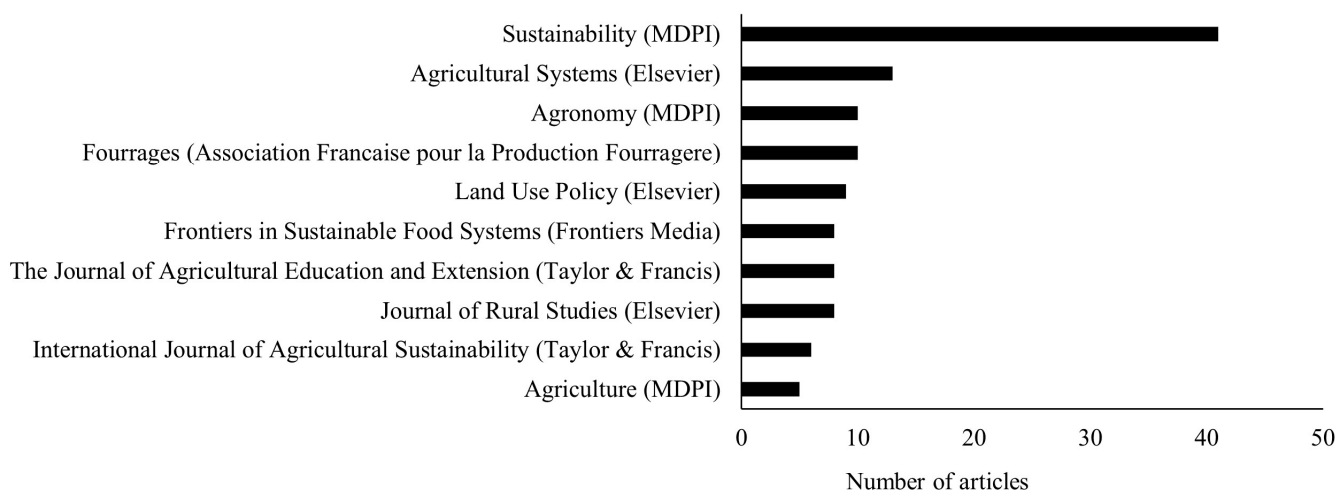


Figure 3. The top 10 journals with the most articles published related to sustainable agricultural practices between 2015 and 2023. (In parentheses: publisher).

It can be seen that 41 of the 118 research articles can be linked to one journal (*Sustainability*), indicating its primary importance in the field. Further journals in the list also

represent the high added value in assessing relevant agricultural issues. Apart from the journal in first place, the distribution of papers among journals (and their publishers) is considered even, which suggests the general relevance of the topic according to the scientific community.

3.2. Practices in Sustainable Agriculture

After the short scientometric introduction, it is worth highlighting the significant characteristics discussed in the literature on sustainable agricultural practices and related fields. It became evident from our review that most authors focus on specific segments rather than overgeneralizing farming issues. According to the literature of the last ten years, authors have determined which agricultural practices and technologies are classified as sustainable. Table 1 highlights some of the most intensely studied aspects of the literature for each year.

The findings in Table 1 suggest that the most studied sustainable agriculture-related aspects in the literature are strongly associated with technological improvements (e.g., the permeation of AI solutions and climate-smart farming technologies). This introduction and distribution of innovations by the scientific community establishes a solid basis for practical implementation, which often lacks theoretical fundamentals, even in some regions with high agricultural potential (e.g., favorable climate and soil characteristics) [83]. It can also be seen that issues are primarily studied as global phenomena; however, geographical involvement in many papers covers regions with much space for agricultural development and efficiency enhancement (e.g., African and Asian territories).

3.3. Types of Sustainable Agricultural Practices

As seen above, evaluating sustainable agricultural practices is a hot topic in the literature. Below, such operations are presented that are considered the most forward-looking and practical based on a meta-analysis of literature findings from the past ten years.

3.3.1. Agroecological Practices

Agroecological practices are methods that integrate ecological principles to create sustainable farming systems. The practices classified in this group emphasize respecting wildlife and the need to maintain an environmental balance [27,50]. In other words, such agricultural practices aim to consistently use natural resources by supporting appropriate and profitable food systems, food safety, and flexibly developing agricultural systems.

The most widely studied techniques include crop diversification, poly-cropping, agroforestry, and the use of local varieties [84], organic fertilizers, intercropping, crop rotation, and cover crops to enhance soil fertility, pest control, and pollination [85,86], and promote organic farming [28]. According to some authors, agroecology-based farms generally provide more ecosystem services than traditional farms, thus improving productivity and promoting environmental health [85]. For instance, in Latin America, agroecological practices have been integrated into broader rural and regional development strategies, supporting socioeconomic development and ecological sustainability [87]. In addition, agroecology also motivates farmers to transform their practices radically, change their thinking, and facilitate participation in local knowledge distribution [88].

For the evaluation of agroecological systems, the Tool for Agroecology Performance Evaluation (TAPE) was developed under FAO coordination to measure the performance of methods concerning governance, culture, health, and nutrition [89]. Preliminary results of TAPE applications show that agroecological practices improve ecosystem services such as soil fertility, pest control, and pollination compared to conventional farming methods. A positive effect on farmers' well-being and food safety, especially in regions with scarce resources and high biodiversity, such as Tanzania and Malawi, was also reported [87,90,91].

3.3.2. Sustainable Agricultural Intensification

Sustainable agricultural intensification refers to a process that enhances the productivity of agricultural land by increasing the yield per unit by adopting various measures, such as automation, innovative plant varieties, and advanced farming techniques [92]. It includes three main components: (i) genetic intensification, which focuses on the improvement of yield, pest resistance, and nutritional quality through precision breeding and genomics; (ii) eco-intensification, which increases general efficiency while respecting environmental conditions and needs; and (iii) socio-economic intensification, which includes market development, political support and social capital construction [93]. The main characteristics of sustainable agricultural intensification are overviewed in Table 2, while some significant barriers to implementation and their policy-assisted potential solution proposals are found below.

Table 2. The main characteristics of sustainable agricultural intensification.

Nr.	Type of Sustainable Agricultural Practice	Components	Aims of Implementation	The Effect on the Production	The Effects on the Environment	Factors Hindering Practical Implication	Source
I.	Sustainable intensification of crop production	(a) Optimization of tillage	It aims to support yield stability by optimizing the water-holding capacity of soils and making farming methods more cost- and eco-efficient.	Increased yield and improved plant fertility.	Contributes to maintaining soil health by minimizing soil characteristics-based disturbance, maintaining soil structure, and providing better soil quality.	Local conditions, soil characteristics, and the economic viability of various soil cultivation methods influence the optimization of tillage methods.	[74,94–101]
		(b) Optimization of water management	It attempts to map multiple supply and demand scenarios using computational techniques and algorithms to set the most optimal water use.	Improved water management efficiency and increased productivity.	Contributes to the protection of water resources, to prevent water waste, and to enhance the quality of water.	The complexity and uncertainty of water systems, the lack of adequate water management policies, the variability of water resources, the economic interests.	[98,101–109]
		(c) Mixed farming integrating crop production and animal husbandry	It focuses on utilizing synergies between plants and livestock, such as nutrient recycling and diversified production, thereby increasing ecological and economic resistance.	Increased productivity and optimized resources by providing healthier flora and livestock and implementing more flexible agricultural systems.	Creates a more balanced ecosystem and supports biological diversity.	Lack of knowledge, skilled workforce, handling of synergies characteristic of mixed systems, uncontrolled material flow.	[98,103,110–115]

Table 2. Cont.

Nr.	Type of Sustainable Agricultural Practice	Components	Aims of Implementation	The Effect on the Production	The Effects on the Environment	Factors Hindering Practical Implication	Source
		(d) Precision crop management	It aims to manage agricultural areas' geographical and temporal diversity, including using advanced technologies to optimize resources and improve yields.	Uses advanced technologies and data analysis, provides more efficient plant treatment, optimized nutrient distribution, and maximized yield, cost savings by the reduced use of chemicals such as fertilizers and pesticides, increased overall profitability.	Contributes to preserving and restoring sensitive and vulnerable habitats. It helps to reduce the environmental impact of farming by minimizing the use of chemicals, conserving water resources, and reducing waste.	High initial cost and energy requirements, lack of knowledge and technical expertise, falsely addressed space-specific features.	[99,116–123]
		(e) Bioremediation	It uses living organisms such as bacteria, fungi, and plants to break down, remove, or transform environmental contaminants into less harmful substances.	More cost-effective compared to traditional clean-up methods as it often requires less equipment and workforce and can be used on a large scale.	Natural metabolic processes of organisms involved in bioremediation organize harmful substances into less toxic or non-toxic substances, promoting the restoration of the natural balance of the environment and improving soil health.	The complexity of microbial processes adversely influences the efficiency of integration, the lack of related knowledge, the type and metabolic activity of the microorganisms used, the high cost, the high variability of environmental factors, slow procedure flow, selectivity for contaminant type.	[98,103,124–134]

Table 2. Cont.

Nr.	Type of Sustainable Agricultural Practice	Components	Aims of Implementation	The Effect on the Production	The Effects on the Environment	Factors Hindering Practical Implication	Source
II.	Integrated Pest Management (IPM)		It seeks to combine cultural, physical, mechanical, biological, and chemical methods to keep pest populations below economic thresholds, thereby minimizing risks to human health and the environment.	Increased yields, reduced pesticide use, and enhanced overall environmental sustainability.	The purpose of these methods is to reduce the dependence on pesticides and to minimize the adverse effects on the environment.	The lack of appropriate knowledge of crop production methods or pests.	[99,135–140]
III.	Integrated Nutrient Management (INM)		It aims to combine organic and inorganic fertilizers to improve soil health and crop productivity sustainably.	Increased yields by improved soil quality, increased nutrient use, and productivity.	Due to its application, soil health can be maintained or improved.	Higher levels of expertise and monitoring compared to traditional methods, the low availability and quality of organic materials, the lack of proper policy support.	[141–148]
IV.	Climate-smart agriculture	(a) Minimum tillage and no tillage (MT and NT)	It supports the decrease in farming intensification by mitigating as much physical impact on the soil system as possible.	Improved agricultural productivity and soil health, alleviated exposure to climate change.	These practices minimize soil disturbances, reduce erosion, enhance soil organic matter content, and improve water infiltration and retention.	Lack of practical knowledge, cost factors, need for special machines, and technological challenges.	[144,149–156]
		(b) Cover cropping	It supports the growing of certain crops primarily for the benefit of the soil rather than for direct harvest.	Improved soil biological activity and health and increased productivity.	It contributes to the quality of the soil by improving its physical, chemical, and biological properties, increasing organic matter and nutrient content, suppressing weeds, and eradicating pests.	High related costs (maintenance), the lack of expertise, and practical knowledge needed to select the appropriate species.	[144,157–164]

Table 2. Cont.

Nr.	Type of Sustainable Agricultural Practice	Components	Aims of Implementation	The Effect on the Production	The Effects on the Environment	Factors Hindering Practical Implication	Source
		(c) Nutrient recycling from livestock	It aims to minimize waste and optimize material use by recirculating reusable materials into different farming phases.	Increased productivity, improved cost-efficiency by recovering secondary, mineral-rich and organic products.	Animal fertilizers are rich in organic matter and nutrients that support the fertility of the soil, and these measures also reduce animal waste, while the involvement of external agents is minimized.	Cultural, educational, and institutional hiatus, technical, and economic constraints.	[144,165–170]

(I) Sustainable intensification of crop production

Sustainable crop intensification practices positively affect yields and farmers' income; however, obstacles to their widespread adoption still exist. One significant barrier is the perception of risk among small producers, who often see new technologies as a risky investment [171,172]. In addition, the lack of participation of agricultural producers in developing such technologies and the absence of a supportive policy environment hinder widespread integration [98]. Ecological concerns, such as land degradation and the adverse effects of previous agricultural intensification practices, are also significant challenges [173]. Insufficient experience with sustainable production concepts and the need for stakeholder-driven approaches to agricultural intensification are realized as additional limitations [174,175]. Like each method listed, the solution should be provided primarily by adequate and tailored policies. Establishing market opportunities and fostering/inhibiting the use of agriculture-related products (e.g., fertilizers and genetically modified seeds) are significant aspects of the process [176].

(Ia) Optimization of tillage methods

Although the literature contains several promising practices, many factors hinder the optimization of tillage methods, including soil compression, the decrease in soil organic matter content, the loss of nutrients required for optimal soil cultivation, and the low economic viability of non-destructive cultivation techniques [177–179]. These diverse challenges require a comprehensive and location-specific approach for optimization, including, among others, nutrient supplementation, soil amendment use, and the timing of field operation, all executed with data collection and calculations based on reliable logging and methods.

(Ib) Optimization of water resources management

The optimization of water resources management faces some significant obstacles, including the complexity and uncertainty of water systems, the lack of adequate water management policies, inadequate decision-making frameworks [180], spatial and temporal changes in water resources, and conflicts between stakeholders [102]. In addition, the consolidation of modeling results and the time-consuming justification process of their efficiency are also significant challenges for adopting best practices with regard to water resources [107]. Therefore, handling these shortcomings requires coordinated efforts

involving advanced optimization techniques, stakeholder agreements, and integrating adaptive management strategies. As actual evidence, resource policies make a significant contribution by recognizing local characteristics (e.g., water stress in the Middle East) and supporting joint technological (e.g., water recycling and reuse, rainwater harvesting, desalination) solutions [181].

(Ic) Mixed farming integrating crop production and animal husbandry

The spread of mixed farming, combining crop production and animal husbandry, is significantly hindered by the high labor intensity and time consumption associated with integrating plant and animal breeding systems [114]. Additionally, the heterogeneity of mixed management systems, high general costs, and initial capital investments into crop production systems are limiting factors [110]. Further, the need to reduce functional interactions between plants and livestock [115] and the availability of a skilled workforce [182] are also weaknesses. In addition, nutrient recycling and the complexity of resource distribution between food, feed, and animal products are challenging, especially in maximizing the efficiency of food production [183]. These should be resolved by supporting policy and complementary training opportunities and subsidies to enable farmers to acquire modern tools and machinery.

(Id) Precision crop management

Despite several technical and economic obstacles, precision crop management techniques hold immense potential for widespread application [184]. Significant barriers include high initial costs and energy requirements, a lack of knowledge and technical expertise, the complexity of managing site-specific inputs, and the challenges of climate and topography. However, with efficient cooperation between science, policymakers, and actors in the agricultural system, these obstacles can be overcome, paving the way for more efficient and sustainable crop management [118,185,186].

(Ie) Bioremediation

Being a promising and environmentally friendly approach to treating environmental pollutants, bioremediation faces several difficulties that hinder its widespread application [125]. These include the complexity of microbial processes, the type and metabolic activity of microorganisms used, the dynamic nature of the environment, and the variability of environmental factors (e.g., availability of nutrients, temperature, pH, toxicity, and concentration of compounds that can adversely affect the bioremediation process) [187]. In addition, bioremediation's nature and efficiency are highly varied by the contaminant type (e.g., inorganic vs. organic), which requires specific knowledge in the field [188]. Many innovative engineering tools, such as remote sensing and GIS-based mapping, support bioremediation practices in determining the degree of contamination. Still, a more intensive interaction of scientific fields and a multidisciplinary approach is also necessary [189]. As polluters lack accountability in many regions of the world due to insufficient legislation, policies should target this shortcoming by creating legal incentives, which would provide a boost to clean-up technologies such as bioremediation [190].

(II) Integrated pest management (IPM)

The extensive manifestation of IPM principles is primarily hindered by their cost and a lack of knowledge. In addition, the increased workload associated with IPM, and the uncertainty of the actual effectiveness of the methods against pests, do not support the spread of these techniques [140]. Overcoming these barriers requires a complex approach that includes better training, economic incentives, and improved communication strategies. The spread of these practices and a reduction in the use of pesticides can, however, best be facilitated by appropriate regulation. For instance, Directive 2009/128/EC of the European Parliament and of the Council aims to reduce the risks and impacts of pesticide use on human health and the environment and to promote integrated pest management and the

use of alternative approaches or techniques to reduce dependency on pesticide use. In 2017, the Commission undertook the development of a consensus in cooperation with the Member States on the development of harmonized risk indicators to monitor trends in the risks arising from the use of pesticides at the EU level [191]. Additionally, in February 2023, within the framework of the “Farmer’s Toolbox for Integrated Pest Management” program, the European Commission developed a toolbox of proven IPM practices. This toolbox encourages national authorities and agricultural actors to use best practice techniques and technologies, such as crop rotation and balanced fertilization, monitoring harmful organisms, targeted and reduced application, and non-chemical pest control methods. The database also contains 273 plant-specific guidelines. In this regard, the European Commission highlighted that reducing the use of pesticides often works best when combined with other goals, such as soil conservation practices, reducing the use of fertilizers, and providing ecosystem services [192].

(III) Integrated nutrient management (INM)

Integrated nutrient management faces many obstacles, despite its proven benefits for sustainable agriculture. One of the significant drawbacks is the dependence on chemical fertilizers [193] and farmers’ lack of awareness and knowledge of the long-term benefits of INM (e.g., improved soil health, increased crop yields, and reduced pollution) [194,195]. In addition, the inconsistent availability and quality of organic materials such as farmyard manure, compost, and bio-fertilizers may also hinder the consistent application of INM practices [196]. A decent solution could be a balanced and site-specific combination of organic and inorganic nutrients, but this would require more expertise and monitoring than conventional methods [197]. Overall, barriers can be removed through education, financial support, improving the supply chain of ecological inputs, and setting stricter policy frameworks. As for the latter, legal documents created at the community and state levels to limit inorganic fertilizer use and foster the application of organic compounds have proven to be efficient [198]. Therefore, adapting best practice policies is key to the efficient sector-level coordination of nutrient use.

(IV) Climate-smart agriculture (CSA) practices

This group of techniques includes conservation agriculture, integrated soil fertility management, plant diversification, and agroforestry, which improve yields and farm income while reducing greenhouse gas emissions [41,199]. CSA practices also include advanced irrigation techniques, such as subsurface drip irrigation, which improve soil properties and increase crop yields [200]. In addition, for example, early planting and using organic fertilizers have been beneficial in drought-prone areas, significantly increasing maize and bean yields [201].

(IVa) Minimum tillage (MT) and no-tillage (NT) management

As realized barriers ahead of this group of methods, the lack of practical knowledge, the initial costs of such practices, and the need for special machines capable of handling different soil hardness and operating speeds have been identified. Further, technological barriers to related solutions can also inhibit these sustainable practices in many regions [154,156]. Recently, policymakers have focused on MT and NT management, which, in a small group of high-income countries, has resulted in incentives toward the continuous implementation of afore management techniques [202].

(IVb) Cover cropping

Although these practices are becoming more and more popular, it is necessary to consider the variability in the costs (e.g., increases in the price of seeds, the high cost of labor and equipment) and the lack of expertise related to the selection of the appropriate cover crop type [161]. Besides these factors, in some cases, the inconsistent effect of cover crops on soil water retention and excessive competition for water between cover plants

and cultivated plants (e.g., in Mediterranean regions) should be assessed appropriately, as these are potential limits to the spread of this practice [203]. Research shows that targeted education programs and cost-sharing initiatives can help alleviate financial problems and promote wider adoption. In addition, selecting less competitive cover plant species and optimizing management practices can reduce interspecific competition [204].

(IVc) Nutrient recycling from livestock

Nutrient recycling from livestock faces many cultural, educational, and institutional challenges, as well as technical and economic limitations. Cultural and educational barriers often stem from a lack of awareness and knowledge about the benefits and methods of manure recycling [205]. Institutional barriers include inadequate policies and regulations that do not encourage nutrient recycling in many regions of the world [206]. Technical challenges cover the complexity of livestock waste processing and specialized technologies supporting efficient nutrient recovery, which is not readily available or affordable for all farmers [168]. Economic factors also play a significant role: costs associated with the transport and distribution of manure, the market demand for recycled manure products, and the lack of quality standards limit the economic viability of nutrient recycling [170]. Addressing these barriers requires a multifaceted approach that includes policy reforms, educational initiatives, and the adaptation of state-of-the-art technologies to promote sustainable recycling of livestock nutrients.

It can be concluded that many factors, including farm size, access to financial resources, and genetic, ecological, and socio-economic intensification components, influence the adoption of solutions. The successful integration of such practices requires an interdisciplinary approach, the involvement of the public and private sectors [207], and more intensive regional cooperation. Further, future progress in sustainable agricultural practices cannot be accomplished without the support of legal frameworks and policies built on local demands.

3.3.3. Sustainable Innovative Agricultural Practices

The practices mentioned above cannot be separated from the technological development routes, as they are also vital to increasing resource efficiency, reducing environmental degradation, and improving agriculture's resilience to climate change. To provide a more detailed but concise thought-provoking overview, Table 3 presents the most decisive and promising practices with the potential for innovation to make agricultural operations more sustainable.

Table 3. The most frequently studied sustainable innovative agricultural practices in the literature.

Nr.	Type of Sustainable Innovative Agricultural Practice	Components	Aims of Implementation	Effects on Production	Effects on the Environment	Factors Hindering Practical Implication	Source
I.	Biotechnology	(a) General biotechnology	Aims to use biological organisms and systems to develop quantitative and qualitative agricultural production for specific farming purposes.	Improved productivity, resilience, effective management of natural resources, and satisfied human nutritional needs.	Biotechnology can create plants resistant to pests and diseases, thereby reducing the need for chemicals to protect the quality of the environment and reducing the use of pesticides through stress tolerance genes.	High related costs, regulatory deficiencies, the lack of social acceptance, and inadequate/outdated infrastructural conditions.	[208–210]

Table 3. Cont.

Nr.	Type of Sustainable Innovative Agricultural Practice	Components	Aims of Implementation	Effects on Production	Effects on the Environment	Factors Hindering Practical Implication	Source
		(b) Genetic engineering	Modifies the genes of organisms to establish characteristics enabling more resilience and productivity under specific conditions.	Improved quality and quantity of crop production, reduced costs, and improved nutrient utilization.	Improve plant properties and strengthen resistance to pests, diseases, and adverse environmental conditions.	Environmental and health consequences include possible allergenic effects, unintended ecological risks, genetic pollution, and a deficit in social acceptance.	[211–219]
		(c) Marker-assisted selection	Operates to enhance crop yield by selecting the most favorable gene alleles using DNA markers, thus improving the targeted trait in the population.	Increased efficiency, reduced costs, accelerated development of improved varieties, improved crop yield, and increased genetic gain of better populations by increasing selection accuracy and reducing generation intervals.	It supports the selection of traits that increase resistance to environmental stress factors, reduce the need for chemicals, and improve resource efficiency.	High costs, lack of expertise, time-scale of development, unsupportive regulations.	[211,220–224]
		(d) Tissue culture and micropropagation	These aim to multiply and regenerate plant materials under laboratory conditions; many individuals with the same characteristics can be cultivated in the field.	More balanced production of seeds, setting priorities for propagation conditions, and better rooting performance.	Optimization of growth conditions by selecting the most appropriate environment for the species.	High costs from testing to application, lack of trained experts.	[225–228]
		(e) Omics	Analyses data on the structure and function of biological systems at specific levels within the fields of genomics, proteomics, transcriptomics, metabolomics, and phenomics.	Improved plant traits (with focus areas such as gene characterization, protein regulation patterns, and metabolite composition) to achieve global food security.	Increases drought tolerance, improves the efficiency of nutrient use and pest resistance.	Regulatory/legal barriers, lack of expertise to carry out extensive research.	[229–233]
		(f) Bioinformatics	Collects, organizes, and processes information on genes and molecules with software to interpret genetic processes to be highlighted during cultivation.	Better seed quality, improved plant resistance, enhanced soil quality, and support of plant-based human disease diagnosis based on large datasets.	Helps the better understanding of the environmental systems as a whole.	Educational difficulties in training scientists, acceptance/adoption of tools, high software and hardware costs.	[234–238]

Table 3. Cont.

Nr.	Type of Sustainable Innovative Agricultural Practice	Components	Aims of Implementation	Effects on Production	Effects on the Environment	Factors Hindering Practical Implication	Source
II.	Tools of eco-efficiency		Considers adopting practices and technologies that operate with low energy consumption and undesired emissions.	Increased crop quality/quantity with reduced resources invested, optimized supply chain, support of technological progress.	Supports reduced resource use resulting in lower emission levels, establishes programs promoting environmental sustainability.	Lack of expertise and holistic/systematic approach, inconsistent legal frameworks, climate change.	[239–244]
III.	Artificial intelligence (AI)		Its integration will provide better calculations, forecasting, and more reliable decisions throughout the agricultural value chain.	Precise and controlled management, including (among others) plant selection, procedure timing, irrigation, weeding, anti-pest measures, and nutrition supply, increased overall production efficiency.	Helps the removal of pests, weather prediction-based software for a more conscious use of renewables, emission tracking to locate pollution sources.	Low social acceptance rate, lack of technological knowledge, lack of strategies.	[194,245–250]
IV.	Drones	(a) Remote inspection and data gathering	Provides more accurate and time-saving solutions for field evaluation.	The identification of diseases, yield loss, and other discrepancies, monitoring of real-time livestock movement, and support of rapid soil and water sampling for plot assessment.	Fosters quick intervention in plant/plantation impairments and directed intervention instead of extensive intervention with environmental deterioration.	High initial and maintenance costs of equipment, need for potential authorization.	[251–256]
		(b) Fertilizer and pesticide application	Enables a precise and timely output of agents to save human workload, time, and overall energy investment.	Directed and reduced use of chemicals for balanced plant development, time-saving compared to conventional methods.	Eliminates the physical burden (e.g., soil deterioration) of heavy machinery.	High equipment initial and maintenance costs, need for potential authorization and social concerns around inappropriate airborne spraying.	[253,255–260]
V.	Satellites		Establishes continuous surveillance of crops for better yield and pest management.	Crop health monitoring, yield assessment, soil mapping, irrigation management, pest and disease control, and overall food security with the potential to increase efficiency by attaching AI and machine learning.	Enables early-stage intervention to avoid environmental deterioration and contributes to the establishment of databases by data collection.	High setup, maintenance, and reparation costs, high energy consumption, lack of expertise, and lack of farmer willingness to implement due to its inaccessible nature.	[261–265]

Table 3. Cont.

Nr.	Type of Sustainable Innovative Agricultural Practice	Components	Aims of Implementation	Effects on Production	Effects on the Environment	Factors Hindering Practical Implication	Source
VI.	Sensors	(a) Optical sensors	Their application is aimed at favoring general crop protection.	Surface reflection- and material-based data collection with installation on different vehicles and tools (e.g., diseases and irrigation requirements).	Indication of unfavorable changes in soil and plant characteristics.	High costs, lack of trained professionals.	[266–268]
		(b) Electro-chemical sensors	Supports the accurate determination of beneficial and undesired ions in soil layers to favor biological processes.	Quantification and qualification of soil parameters (e.g., pH, ion composition, and concentration) and monitoring pollution spread and hot spots.	Real-time overview of soil health to maintain an adequate habitat for species.	Laboratory infrastructure required for further soil analyses.	[269–271]
		(c) Mechanical sensors	Determines the physical properties of soils to maintain adequate structure.	Assessment of mechanical soil parameters by evaluating physical resistance.	Determines the location of areas affected by undesired soil compaction to prevent irreversible damage to soil organisms.	High cost of tools, lack of technical personnel.	[272,273]
		(d) Dielectric sensors	Aims to determine soil water conditions and supports the setting of proper moisture values.	Determination and adjustment of soil and tissue moisture levels for appropriate plant development.	Helps determine sites sensitive to drought and monitor seasonal changes in the soil water phase.	High cost of tools, lack of technical personnel.	[274–277]
		(e) Location sensors	These are applied to prevent the effects of unfavorable weather conditions on crops.	Information on environmental (primarily weather) conditions based on GPS data.	The sensors log data in different intervals to create a time series of information (e.g., being practical for climate change studies).	High tools, data storage, processing costs, and a lack of proper interpretation of results due to insufficient training.	[272,278,279]
		(f) Air-flow sensors	Determines the physical properties of soils to maintain adequate structure.	Data collection regarding various soil parameters by penetrating air into the depths.	A comprehensive evaluation of soil characteristics aids farming efficiency and provides data for science-related research.	High costs of tools and lack of farmers' information on specific devices and functions.	[273,280,281]
VII.	Forecasting systems	(a) Weather forecasting systems	Helps avoid the detrimental consequences of weather/ environmental extremes by enabling premature preparation.	Preparation for indices risking crop health and food safety, decreased import/transportation dependency due to the realization of projected yield.	Managers of adjacent sites can also be involved in the data access to broaden the range of areas with protective measures against forecasted weather phenomena (e.g., hail).	High cost of the establishment of a network of units and the high cost of tools needed for the prevention.	[282,283]

Table 3. Cont.

Nr.	Type of Sustainable Innovative Agricultural Practice	Components	Aims of Implementation	Effects on Production	Effects on the Environment	Factors Hindering Practical Implication	Source
		(b) Market forecasting systems/models	Aims to inform stakeholders on future processes by past and recent data processed with statistical analyses, aids the potential restructuring of the cultivation portfolio.	Indication of the short- and mid-term changes in product prices, whereby the individual agricultural portfolios can be restructured.	Monocultural cultivation depletes soil nutrients, while intermittent crop rotation can positively influence physicochemical soil properties.	Lack of relevant economic/scientific knowledge, insufficient/nonreliable raw data results in biased outcomes, nonresilient farming structures.	[284–286]
VIII.	Simulations		Aims to present possible future scenarios based on past data for farmers.	Scenarios for crop yield and quality, water and fertilizer use, and weather conditions to support efficient adaptation and mitigation measures in farming.	Simulations predict changes in climate parameters, whereby local and regional scenarios can be formed regarding the potential environmental consequences.	Insufficient input data (quantity and quality), high software costs, and the lack of trained experts.	[287–289]
IX.	Big Data		Supports modern, data-based farming operations with reliable information.	Reliable forecasting and decision-making, assessment of water use, and optimization of energy and costs, enhanced product safety.	Access to extensive data and its appropriate interpretation also support minimizing environmental burden by proposing farming practices with the least stress exerted.	Data security concerns among farmers, lack of human and financial resources, and low technological maturity level.	[290–292]
X.	Special vehicles		Aims to provide machinery in any cultivated area to broaden the range of arable lands and enhance the quality of farming operations.	Increased accuracy and decreased loss by planting and fertilizing, increased harvesting efficiency with time-saving operation.	Lower emission than conventional vehicles, a more efficient operation requiring less resource use.	Fear of environmental threat, low adaptation to novel solutions, local regulations, high costs.	[293–296]
XI.	Nanotechnology		Enables the improvement of desired traits of tools by implementing state-of-the-art technologies.	Improved crop quantity, quality, and security, support of the controlled application of soil/plant fertilizers and amendments, and more efficient agricultural operation through the value chain.	Enables decreased resource use (e.g., raw materials), energy generation from renewables (e.g., solar panels), and contamination remediation using nanomaterials.	Lack of expertise, health risks upon misuse of persistent nanomaterials, and high related costs.	[297–301]

Table 3. Cont.

Nr.	Type of Sustainable Innovative Agricultural Practice	Components	Aims of Implementation	Effects on Production	Effects on the Environment	Factors Hindering Practical Implication	Source
XII.	Innovative seeds		Aims to develop seeds with better characteristics in terms of resilience and yield.	Increased stress tolerance, higher yield, shorter cultivation periods, and better product transportability and keepability.	Due to the seeds' benefits, lower amounts of water and fertilizers are required, and transportation routes are shorted by cultivation in areas formerly considered infertile.	Regulation of (genetically) modified crops, low innovation willingness/uncertainty of farmers, lack of knowledge.	[302–305]
XIII.	Innovative food production systems		Helps provide food in remote areas with resource deficiencies, replace foods in the diet with less ecological footprint.	Market establishment by novel foods and foods with novel methods, increasing demand triggers higher production quality and quantity standards.	Contribution to decreased water consumption (e.g., plant-based meats), direct and indirect enhancement of consumers' environmental consciousness.	Aversion of consumers, sluggish licensing and regulation of products, high developmental costs, and lengthy experimental procedures.	[306–308]

It is worth noting that the classifications above are not considered a universal and exhaustive listing; however, these highlighted segments appear in the literature the most frequently and, according to several authors, have a core role in forming recent and future advances in agriculture. Thus, the transition to more sustainable agriculture is determined by integrating novel technologies (e.g., AI, drones), which, upon successful implementation, will significantly contribute to the eco-efficient operation of the sector. However, the actual adoption of these solutions is burdened by several common challenges. Based on the classifications in Table 3, a short overview of the most frequently highlighted issues can be found below.

(Ia) General biotechnology

The spread of biotechnology faces several financial, regulatory, social, and infrastructural obstacles. High investment and production costs represent significant economic and regulatory challenges, as different national and international regulatory frameworks form trade barriers. Among the difficulties, various levels of social acceptance of technologies can be underlined, hindering innovations' market integration [309–311].

(Ib) Genetic engineering

As Table 3 indicates, several environmental and health concerns may arise from the use of genetically modified organisms [216]. Partly due to these potential risks, the social acceptance of the genetic modification of organisms is also low. As a first phase, a solid regulatory framework is essential for initial support in integrating this technology. At the same time, well-founded information has to be published to a wider breadth of society to help people be more informed and thereby provide sufficient background for individuals to distinguish between actual and presumed concerns.

(Ic) Marker-assisted selection

Obstacles to the practical spread of marker-assisted selection include, among others, the high costs associated with genotyping a large number of plants, the low economic return on investment in the breeding of plant species, and the limited knowledge of the technical features [219,220,222]. In addition, this technology is considered adequate in the case of testing properties that can be measured only to a limited extent [312]. Therefore,

specific subsidies and governmental programs should support the spread of such scientific initiatives, with significant expenditures in the research and development procedures.

(Id) Tissue culture and micropropagation

Like marker-assisted selection, tissue culture and micropropagation adoption face multiple challenges. Knowledge and expertise in this domain are still moderate among farmers, which does not form sufficient demand and hinders the execution of extensive laboratory experiments. Thus, the crop yield and overall market competitiveness remain lower than for those areas with massive scientific backgrounds (e.g., biotechnology) [313]. According to some authors, the education of scientists, professionals, and farmers, along with complementary regulatory support, would be giant steps toward resolving these barriers, and rectifying the significant lagging of this area [228].

(Ie) Omics technologies

Despite the advances in genomics, proteomics, transcriptomics, metabolomics, and phenomics demonstrated in Table 3, challenges such as public perception, an immature regulatory environment, and a lack of robust training and capacity building remain. Further, compliance with data sharing and privacy standards often hinders the adequate exploitation of technological potential [314]. Additionally, the lack of standardization and efficient analytical methods due to insufficient resources are significant factors to eliminate [315]. These require transparent communication and substantial investment in research and development to realize the full potential of agricultural biotechnology [224]. Therefore, the penetration of omics technologies would greatly benefit from loosening regulatory frameworks based on scientifically supported decisions and presenting this information on multiple societal scales.

(If) Bioinformatics

As shown in Table 3 above, a wide range of modern approaches has been considered in the scientific literature. Bioinformatics enables the interconnectivity of specific farming practices, thereby providing all-pervasive technological solutions surrounding food safety, both in quality and quantity. However, many bioinformatics implementations face difficulties arising from insufficient educational systems and the lack of individual competencies (e.g., simultaneous biological and informatics knowledge), which are additional barriers besides the high emerging costs [238]. These obstacles can be widely overcome by fostering digital progress on each level of the educational system, whereby a higher number of professionals can be trained with dual (biology-informatics) interests.

(II) Tools of eco-efficiency

The problems raised regarding agricultural eco-efficiency are multifold, specifically since the measures of eco-efficient operation (modern technologies to reduce environmental burden) can cover nearly all segments of agricultural sustainability. This approach can seem overgeneralized; however, barriers are often related to the limitations of individual tools (see below). To highlight some of the most common issues, the low number of trained personnel, the challenging and sometimes contradictory regulatory frameworks, and climate change are the primary aspects to address. As these concerns emerge, a systematic approach is required across societal and economic perspectives. Approaches should focus on adopting the best available techniques implemented by appropriately qualified professionals, keeping, at the same time, societal, economic, and ecological demands in mind [239].

(III) Artificial intelligence (AI)

While it possesses immense potential in agriculture, artificial intelligence is considered to have many barriers to its implementation in the field. AI's relatively novel methods are still scarcely known and bear social uncertainty. Users' skills are usually insufficient, aggravated by the lack of joint strategies. Further, data quality issues and ethical concerns are

also barriers to AI integration. These shortcomings could be efficiently handled by uniform legislation and related attitude formation of affected parties, providing a framework and knowledge enabling conscious decisions in its application, even in farming practices [316].

(IV) Drones

The use of drones provides a wide range of benefits in farming. However, factors like high costs and regulation hinder their extensive use among farmers. The concerns linked to drones are enhanced in cases when they are used for chemical agent application; spraying into the atmosphere is considered a health risk by many people. Therefore, general governmental and regulatory confirmation would be needed to emphasize advances and resolve the doubt regarding the presumed hazards, highlighting the benefits, drawing the scope of application, and triggering the sparing use of drones and chemicals [260].

(V) Satellites

The barriers to the application of satellites comprise the need for high financial, energetic, and expert investment into the technology, whereby these technologies are attainable only for major institutions possessing these resources. Some mapping services are also available for public use, but the skills required for proper interpretation of the information are often lacking. Training should be directed at farmers to aid this concern, during which basic information on the appropriate use of satellite images in their agricultural practices should be forwarded. Further, primary sources for such data should also be reflected on, which help farmers gather as much relevant data as possible [264].

(VI) Sensors

Using sensors gives a thorough overview of the relevant processes in soil and vegetation. However, the application level of these instruments remains below a certain standard. Unfortunately, farmers' economic opportunities and know-how in several geographical areas enable them to use only a few or none of these during general fieldwork. This means that the first challenge is to get the farmers familiar with the instruments available for data collection, fostering the exchange of information. These measures should be followed by establishing funds for a dedicated governmental budget to help procure essential tools [285,289].

(VIIa) Weather forecasting systems

The formation of weather forecasting systems is burdened primarily by high costs related to the weather/environmental forecasting apparatus. Along with this, regional differences can be perceived in this field regarding the actual infrastructure and background expertise, raising the need for governmental intervention. However, in many countries, efficient bound forecasting and averting systems are already in operation (e.g., hail forecasting), providing up-to-date information to farmers. Analogous to this, more weather phenomenon-related cross-boundary forecasting systems should be installed and maintained with easily attainable online information for all stakeholders [317].

(VIIb) Market forecasting systems

The use intensity of this type of forecasting has barely been examined; however, the reliability of sources for relevant information, the ability of farmers to evaluate the credibility of data, and even the continuously changing economic environment make it extremely difficult to assess the actual role of market forecasting systems. While the data quality and critical attitudes in this area can be enhanced, the uncertainty of the economy cannot be eliminated, and this remains a major weak spot [284].

(VIII) Simulations

Using simulations can be beneficial for planning farming management schemes; however, some factors prevent the efficient use of technology in this domain. Data given as input lack adequate quality and quantity in many cases, which should be eliminated by standardized measurements, resulting in validated outcomes that are easily accessible

for further use. Fluent data processing of simulations has high software and hardware costs. Therefore, the license and technical guidance for their use should be integrated into services tailored to farmers (e.g., bank products) to encourage their use and thus favor food safety [318].

(IX) Big Data

Integrating Big Data (e.g., huge and progressively increasing amounts of data on environmental/cultural parameters) has already penetrated agricultural practices. Still, its comprehensive application is limited by data quality and security and human and financial resource-based and technological issues. Long-term data storage should be fostered by establishing dedicated, cloud-based data platforms with continuous data input, basic tutorials, and calculation proposals to aid the utilization of information gathered during farmers' operations. With such systems available, human resource dependencies could be sharply decreased, and with targeted agricultural subsidies for each farmer, technological barriers should also be eliminated [319].

(X) Special vehicles

The agricultural use of special vehicles has proved to provide high farming efficiency. However, conservative approaches from farmers, the fear of environmental deterioration caused, regulative hindrances, and high purchase and maintenance costs all counteract the widespread application of such machinery. To move forward, a thorough conversation should be conducted among developers, legal representatives, and farmers to map the needs and opportunities in each potential case. After outlining the aforementioned conditions, future measures could include the publication of relevant agricultural tenders and policy revisions [294].

(XI) Nanotechnology

Practices in nanotechnology have the potential to revolutionize agricultural production. Along with this feature, some significant concerns around its use are highly related to those presented for biotechnology. The lack of expertise, the health risks associated with the materials used, and the high emerging costs hinder its general integration. Considering these obstacles, actions should focus on training groups of researchers for nanotechnological applications and promoting the development of materials and products to eliminate their health-threatening characteristics. Then, after familiarizing farmers with fundamental information, forming demands should be followed by governmental legal and financial support [320].

(XII) Innovative seeds

The development of innovative seeds has had immense relevance during the recent decades of barely predictable climate change patterns. While a great proportion of farmers still insist on conventional solutions, the societal and legal doubt around genetically modified organisms and a significant knowledge gap leave huge unexploited potential in this technological direction. These obstacles are not often set aside. However, reliable and convincing scientific information on the actual ecological and health risks bound to genetically modified organisms (GMOs), and thereby reconsidered legislation, would shift the recent state toward a more open reception of innovative seeds from both farmers and consumers [305,321].

(XIII) Innovative food production systems

The appearance of foods in the market produced using innovative/alternative methods (e.g., underground horizontal or rooftop farming, vertical farming, urban agriculture) has occurred in direct response to unsustainable food supply schemes (e.g., long-distance shipping with economic and ecological concerns) that have predominated previously. These unconventionally produced foods can feed populations remote from conventional food production with novel methods that have decreased ecological footprints. However, there

is much debate regarding the actual sustainability benefits of some of these (e.g., vertical farming and its high related energy intensity). Additionally, with the features above being highly advantageous, consumers still strongly resist food innovation due to production technology-based deviations in taste, consistency, and individual conviction. Moreover, developing and licensing products takes a long time, slowing down their distribution. Science and nutrition-based popularization of these foods would influence the social acceptance of these novelties. At the same time, additional support for the development and shortening of the licensing procedure of foods should also be beneficial to distribution and guaranteeing food safety in the long run [307,322].

According to the literature, each of the technologies above has a particular potential to elevate agricultural production's efficiency and climate resilience. At the same time, farmers have individual opportunities and preferences regarding their operation. The most efficient exploitation of resources requires the education of farmers and smallholders regarding the technological and methodological options via professional assistance, through which specific demands are shaped. Once the future progress directions are formulated, legislation complemented with tailored financial subsidies should be made available for farmers. This would aid more sustainable and efficient operations that serve high-scale agricultural objectives.

4. Conclusions

This study aimed to evaluate significant trends and progress directions in sustainable agriculture, focusing on integrating novel technologies into the sector's operation. This meta-analysis-based literature review relied on a list of 44,629 items published between 2015 and 2023, which was, through screening and eligibility assessment, narrowed down to 291 papers. Further analyses of these publications indicated a yearly improvement in the number of manuscripts, while the quantitative distribution of publications was uneven among the journals. It was found that many techniques are available to foster agricultural sustainability. However, adopting these innovative solutions faces multiple challenges, which hinder their deeper penetration and, thus, the better utilization of technological opportunities. Limitations of this nature also have economic, social, and governmental aspects. Among the most common barriers, high related investment costs, unwillingness to innovate, social awareness, acceptance, and impenetrable legal frameworks were mentioned in several cases. The complexity of the limitations above justifies the need for joint, intersectoral measures to aid agriculture prospects. This study provides insight into the prevailing agricultural processes and localizes focus areas to advance future investigations. These aspects should be addressed even more to help farmers with practical implementation in order to keep up with the expectations of the changing natural, social, governmental, and economic environment. Future environmental legislation and associated financial subsidies must also be directed to favor the evolution of agriculture-related sustainability progress.

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Abbreviations

AI	Artificial intelligence
CA	Conservation agriculture
CRA	Climate-resilient agriculture
CSA	Climate-smart agriculture
FAO	Food Agricultural Organization
GAP	Good agricultural practices
GHGs	Greenhouse gases
INM	Integrated Nutrient Management
IPM	Integrated Pest Management
MT	Minimum tillage
NT	No tillage
SA	Sustainable agriculture
SAE	Sustainable agricultural extensification
SAI	Sustainable agricultural intensification
SDGs	Sustainable Development Goals
TAPE	Tool for Agroecology Performance Evaluation

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