REDUCING THE CARBON FOOTPRINT OF FIELD CROPS: A COMPREHENSIVE REVIEW OF STRATEGIES AND INNOVATIONS

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(Received 3rd May 2025; accepted 16th Jun 2025)

Abstract. In the face of mounting environmental challenges and the imperative for sustainable agriculture, this review explores innovative approaches to reducing the carbon footprint of field crop production. Field crops, essential for global food security and economic stability, contribute significantly to greenhouse gas emissions through conventional agricultural practices. This review assesses the carbon footprint of various field crop production practices, identifies critical sources of greenhouse gas emissions, and explores sustainable farming methods that enhance soil health and promote carbon sequestration. Key areas of focus include the integration of precision farming technologies, the adoption of renewable energy sources, and the implementation of circular economy principles. By evaluating energy-efficient practices and advanced technological innovations, this review provides comprehensive insights and practical recommendations for decision-makers to support the transition to low-carbon agricultural systems. The aim is to foster climate resilience and sustainable agricultural practices, thereby contributing to global efforts to mitigate climate change.
Keywords: *field crop production, carbon footprint, sustainable agriculture, precision farming, circular economy*

Introduction

Overview of the importance of field crop production

Field crops, including cereals, legumes, and oilseeds, are fundamental to global food security and economic stability. These crops occupy vast agricultural areas and provide essential nutrients and raw materials for human consumption, livestock feed, and industrial uses (FAO, 2019). The significance of field crop production is underscored by its contribution to both calorie and protein intake of populations worldwide. For instance, cereals alone account for more than 50% of the global calorie intake (FAO, 2020). As such, ensuring the sustainability of field crop production is paramount for meeting the growing demands of an increasing global population. Furthermore, field crops play a crucial role in the livelihoods of millions of smallholder farmers, particularly in developing countries, where agriculture forms the backbone of rural economies (World Bank, 2020).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2304_76417661

The role of field crops in the context of climate change

Climate change presents significant challenges to agricultural systems, particularly field crop production. Changes in temperature, precipitation patterns, and the increased frequency of extreme weather events can adversely affect crop yields and quality (Lobell et al., 2011). For example, elevated temperatures can accelerate the phenological development of crops, potentially reducing grain filling periods and yields (Tao et al., 2013). Additionally, altered precipitation patterns can lead to either water stress or excess water conditions, both of which negatively impact crop productivity (Rosenzweig et al., 2014). It is important to distinguish between these terms: drought stress is a climatic phenomenon resulting from insufficient precipitation, whereas water stress is a broader concept referring to an imbalance where water demand exceeds the available supply, which can be exacerbated by factors like inefficient irrigation or soil degradation.

Field crops are not only impacted by climate change but also contribute to it through greenhouse gas (GHG) emissions. Globally, the Agriculture, Forestry, and Other Land Use (AFOLU) sector is a major source of emissions, accounting for approximately 23% of total net anthropogenic GHG emissions (IPCC, 2019). Field crop production is a key component of these emissions, primarily through soil management, fertilizer use, and energy consumption. The production processes involved in field cropping, such as soil cultivation, fertilization, and irrigation, result in emissions of CO_2, CH_4, and N_2O, which contribute to the overall carbon footprint of agriculture (Smith et al., 2008). Specifically, the use of synthetic fertilizers is a major source of N_2O emissions, a greenhouse gas with a global warming potential approximately 298 times that of CO_2 over a 100-year period (IPCC, 2014). Furthermore, beyond contributing to global climate change, elevated greenhouse gas emissions, particularly CO_2, have been empirically linked to increased inefficiencies within the agricultural system itself, such as higher post-harvest losses in certain regions, underscoring the multifaceted impact of agricultural emissions (Wang et al., 2024).

Objectives and scope of the study

This study aims to explore strategies and innovations to reduce the carbon footprint in field crop production, thereby contributing to sustainable agricultural practices and climate resilience. The specific objectives include:

1. Assessing the Carbon Footprint: Evaluating the sources and magnitudes of GHG emissions associated with various field crop production practices. Understanding these sources will help identify critical control points for mitigation (Garnett et al., 2013).
2. Energy Efficiency and Renewable Energy: Identifying and promoting energy-efficient practices and the adoption of renewable energy sources in field crop farming. For example, solar-powered irrigation systems can reduce dependence on fossil fuels (Burney et al., 2010).
3. Sustainable Farming Practices: Investigating sustainable farming methods that enhance soil health, promote carbon sequestration, and reduce dependency on synthetic inputs. Practices such as conservation tillage and cover cropping have been shown to increase soil organic carbon stocks (Lal, 2004).
4. Technological Innovations: Exploring the role of advanced technologies, such as smart agriculture and IoT, in minimizing the carbon footprint. Precision agriculture can reduce fertilizer use by 10–20% and increase yields by 10–15%, resulting in a

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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15–20% reduction in GHG emissions from fertilizer application (Gebbers and Adamchuk, 2010; Liakos et al., 2018).

5. Policy Recommendations: Providing practical strategies and policy recommendations to support the adoption of low-carbon practices in field crop production. Policies that incentivize sustainable practices can enhance adoption rates (Pretty et al., 2018).

By addressing these objectives, this study aims to offer comprehensive insights into reducing the carbon footprint in field crops, thereby fostering sustainable agriculture and mitigating the impacts of climate change.

Carbon footprint and agriculture

What is a carbon footprint?

A carbon footprint is a measure of the total amount of greenhouse gases (GHGs) emitted directly or indirectly by a particular activity, product, or organization, expressed in terms of carbon dioxide equivalents (CO_2e) (Wiedmann and Minx, 2007). This metric includes emissions of CO_2, methane (CH_4), nitrous oxide (N_2O), and other GHGs, which contribute to global warming and climate change (IPCC, 2014). Understanding the carbon footprint of agricultural practices is crucial for developing strategies to mitigate their environmental impact and enhance sustainability.

Agriculture, Forestry, and Other Land Use (AFOLU) activities significantly contribute to global greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC, 2019), AFOLU accounts for approximately 23% of total net anthropogenic GHG emissions. Within this sector, the primary sources of emissions include synthetic fertilizers, energy consumption, and soil management practices. A more detailed breakdown reveals that synthetic fertilizers contribute approximately 13% of AFOLU emissions, primarily through nitrous oxide (N_2O) release (*Table 1*). Energy consumption, encompassing the use of fossil fuels for machinery and irrigation, accounts for about 17% of AFOLU emissions. Soil management practices, such as tillage and cultivation, contribute roughly 11% through the release of CO_2 and CH_4. Understanding these proportions is crucial for developing targeted mitigation strategies to reduce the carbon footprint of field crop production.

Table 1. *Contribution of various sources to GHG emissions in AFOLU sector*

GHG Emission Source	Percentage of AFOLU Emissions	Primary GHGs Emitted
Synthetic Fertilizers	13%	N_2O
Energy Consumption	17%	CO_2
Soil Management Practices	11%	CO_2, CH_4
Livestock	44%	CH_4, N_2O
Deforestation and Land Use Change	15%	CO_2

(IPCC, 2019)

The contribution of field crop production to the carbon footprint

Field crop production contributes significantly to the overall carbon footprint of agriculture through various processes:

1. Synthetic Fertilizers: The production and application of synthetic nitrogen fertilizers represent one of the largest sources of GHG emissions within field crop

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production. This is primarily due to the release of nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential approximately 298 times that of CO_2 over a 100-year period (IPCC, 2014). Globally, agricultural soil management, largely driven by nitrogen fertilizer application, accounts for more than half of all anthropogenic N_2O emissions (Snyder et al., 2009). Therefore, strategies targeting fertilizer efficiency are critical for meaningful carbon footprint reduction.

2. Energy Consumption: The use of fossil fuels to power agricultural machinery, irrigation systems, and processing facilities contributes to CO_2 emissions. The energy-intensive nature of these activities significantly increases the carbon footprint of field crop production (Hillier et al., 2009). For instance, the use of diesel-powered tractors and machinery is a key source of CO_2 emissions (Pimentel et al., 2005).
3. Soil Organic Matter Decomposition: Soil management practices, such as tillage, can enhance the decomposition of organic matter, releasing CO_2 and CH_4 into the atmosphere. Conservation tillage and no-till practices have been promoted as ways to reduce these emissions and increase soil carbon sequestration (Lal, 2004). Indeed, comparative life cycle assessments focusing on specific crops like winter wheat have quantified these differences, demonstrating that reduced tillage and direct sowing systems can significantly lower the carbon footprint compared to conventional tillage, primarily through reduced fuel consumption and potential increases in soil carbon sequestration, although economic trade-offs in life cycle costs may also exist (Holka et al., 2020).

Environmental impacts of different field crops

Different field crops have varying impacts on the environment depending on their cultivation practices and resource requirements:

1. Cereals: Crops like wheat, rice, and maize have substantial carbon footprints due to intensive irrigation and fertilizer use. For example, rice paddies are significant sources of CH_4 emissions due to anaerobic decomposition in flooded fields (Yagi et al., 1996). Moreover, the large-scale production of cereals often involves significant inputs of nitrogen fertilizers, contributing to N_2O emissions (Snyder et al., 2009).
2. Legumes: While legumes, such as peas and lentils, are known for their nitrogen-fixing ability, reducing the need for synthetic fertilizers, their overall carbon footprint can still be significant depending on cultivation practices (Jensen et al., 2012). The ability of legumes to fix atmospheric nitrogen can lead to reductions in fertilizer-derived GHG emissions, but this benefit can be offset by emissions from other agricultural practices.
3. Oilseeds: Crops like soybeans and rapeseed have diverse environmental impacts, influenced by factors such as land use changes and energy inputs. The expansion of soybean cultivation, for instance, has been linked to deforestation in tropical regions, which contributes to substantial CO_2 emissions (van der Werf et al., 2002). Additionally, the processing and transportation of oilseeds further contribute to their carbon footprint.

Understanding these impacts is essential for developing targeted strategies to mitigate the carbon footprint of field crops and promote sustainable agricultural practices.

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Energy efficiency in field crop production

Energy conservation techniques in agriculture

Energy Conservation in agriculture involves adopting practices that minimize energy use while maintaining or improving crop yields. Several techniques have been developed to enhance energy efficiency:

1. Conservation Tillage: This technique reduces the number of tillage passes required, thereby lowering fuel consumption and soil disturbance. Studies have shown that conservation tillage can reduce energy use by up to 50% and GHG emissions by 20–30% compared to conventional tillage (Lal, 2004; Holka, 2020).
2. Crop Rotation: Implementing crop rotations can improve soil health, reduce the need for chemical inputs, and enhance energy efficiency. Diverse crop rotations can break pest cycles and improve nutrient availability, leading to lower energy use for pest control and fertilization (Horowitz et al., 2010).
3. Efficient Irrigation Systems: Using advanced irrigation technologies, such as drip or micro-sprinkler systems, can significantly reduce water and energy use. Drip irrigation can reduce water use by 30–50% and energy consumption by up to 30% compared to traditional surface irrigation, while also reducing associated CO_2 emissions (Burney et al., 2010).

Renewable energy utilization in farming practices

Integrating renewable energy sources into farming practices can reduce reliance on fossil fuels and decrease greenhouse gas emissions:

1. Solar Energy: Solar panels can be installed on farms to power irrigation systems, greenhouses, and other equipment. Solar-powered drip irrigation systems have been shown to enhance energy efficiency and reduce carbon footprints (Burney et al., 2010).
2. Wind Energy: Wind turbines can generate electricity for farm operations, especially in areas with consistent wind patterns. Wind energy can be used to power various farm machinery and contribute to overall energy independence (Sørensen, 2004).
3. Biomass Energy: Agricultural residues, such as crop waste and manure, can be converted into bioenergy. Biogas production through anaerobic digestion is a viable option for utilizing organic waste, providing a renewable source of energy for heating and electricity (Lantz et al., 2007).

Assessment of energy-efficient machinery

Investing in energy-efficient machinery can lead to significant reductions in energy use and operational costs:

1. Tractors and Harvesters: Modern tractors and harvesters are designed with energy efficiency in mind, incorporating advanced engine technologies and precision farming tools. These improvements can reduce fuel consumption and enhance overall productivity (Jensen et al., 2024).
2. Precision Agriculture Tools: Technologies such as GPS-guided equipment and variable rate technology (VRT) optimize input use, reducing the energy required for planting, fertilizing, and harvesting. Precision agriculture can result in substantial energy savings and increased crop yields (Gebbers and Adamchuk, 2010).

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3. Energy-Efficient Greenhouses: Utilizing energy-efficient designs and materials in greenhouse construction can reduce heating and cooling needs. Innovations such as double-glazed windows and thermal screens help maintain optimal growing conditions with lower energy inputs (Nelson, 2012).

Sustainable farming practices

Intercropping and agroforestry

Intercropping and agroforestry are increasingly recognized as effective strategies for reducing the carbon footprint of field crops. Intercropping, the practice of growing two or more crops in close proximity, enhances biodiversity, improves nutrient use efficiency, and can increase overall productivity (Jensen et al., 2012). Agroforestry, which integrates trees and shrubs into agricultural systems, provides multiple benefits, including carbon sequestration, soil erosion control, and improved water management (Nair et al., 2010). These practices not only mitigate climate change but also enhance the resilience and sustainability of agricultural systems. Studies have shown that agroforestry systems can sequester 0.2-15 Mg C ha^{-1} $year^{-1}$, depending on the climate, tree species, and management practices (Nair et al., 2010).

Enhancing soil health and carbon sequestration

Sustainable farming practices aim to improve soil health and increase carbon sequestration. Techniques such as cover cropping, crop rotation, and organic amendments enhance soil structure and fertility, promoting carbon storage and reducing greenhouse gas emissions. These practices not only mitigate climate change but also improve crop yields and resilience. According to Olawepo et al. (2024), enhancing soil carbon sequestration in the Global South involves the roles of microbes and biological matter. Tao et al. (2024) highlight the potential of cotton byproduct-derived biochar as an effective amendment for soil improvement and carbon sequestration. Pakhira and Singh (2024) emphasize that increasing carbon stocks in agricultural and forest soils is crucial for climate change mitigation and ecological security.

Organic farming methods and biological pest control

Organic farming systems can reduce overall GHG emissions by 18–25% per unit area compared to conventional systems (Pimentel et al., 2005). Biological pest control involves using natural predators, parasites, and pathogens to manage pest populations, reducing the need for chemical interventions. This approach promotes biodiversity and ecosystem health while ensuring crop protection. Baker and Green (2020) highlight the importance of integrated pest management (IPM) in organic farming. Nchu (2024) emphasizes the importance of sustainable biological control methods, such as classical biological control, conservation biological control, and augmentation biological control, to manage pests effectively.

Sustainable water management strategies

Effective water management is crucial for sustainable agriculture. Strategies include rainwater harvesting, efficient irrigation techniques, and water recycling. These practices help conserve water resources, reduce runoff, and maintain soil moisture levels, ensuring that crops receive adequate water while minimizing waste and environmental impact.

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According to Han et al. (2024), evaluating sustainable water management strategies using TOPSIS and fuzzy TOPSIS methods addresses global water scarcity by comparing rainwater harvesting, water recycling, and desalination across criteria such as water efficiency, cost-effectiveness, environmental impact, social equity, and technological feasibility. The study highlights rainwater harvesting as the most balanced option, excelling in social equity and environmental sustainability. Additionally, Hasan et al. (2023) emphasize the importance of integrated water resource management and community engagement for sustainable water management. Efficient irrigation systems, such as drip irrigation, not only conserve water but also reduce energy consumption and associated CO_2 emissions. Moreover, improved water management, particularly in rice paddies, can decrease methane emissions by avoiding prolonged flooding (Yagi et al., 1996). For example, alternate wetting and drying (AWD) techniques in rice cultivation have been shown to reduce methane emissions by up to 48% without significant yield loss (Zhao et al., 2024).

Waste management and recycling in field crop farming

Effective waste management practices

Effective waste management in field crop farming involves implementing strategies to minimize waste generation, enhance resource efficiency, and promote environmental sustainability. The following practices are integral to effective waste management:

Crop Residue Management: Managing crop residues such as stalks, leaves, and husks is crucial for reducing waste and enhancing soil health. Techniques like mulching, incorporating residues into the soil, and using residues as animal feed or bioenergy sources can significantly reduce waste. According to El-Ramady et al. (2022), agro-wastes can be managed as sources for bioactive compounds, biofertilizers, biomaterials, nanomaterials, pharmaceuticals, and medicinal agents1. These practices not only reduce pollution but also enhance soil health and crop productivity.

Animal Manure Recycling: Recycling animal manure as fertilizer is an effective way to manage waste and enrich soil fertility. Manure can be composted or directly applied to fields, reducing the need for synthetic fertilizers. A bibliometric analysis by Hollas et al. (2022) highlights the potential of animal manure management pathways toward a circular economy. The study emphasizes the benefits of using animal manure for nutrient cycling, soil fertility enhancement, and environmental sustainability. Additionally, Rout et al. (2022) discuss the sustainable valorization of animal manures via thermochemical conversion technologies, which includes processes like pyrolysis and gasification. These technologies not only manage waste effectively but also produce valuable by-products such as biochar, syngas, and bio-oil, which can be utilized for energy production and soil improvement.

Biochar Production: Converting agricultural waste into biochar through pyrolysis is a sustainable waste management practice. Application of biochar can sequester up to 2.5 t CO_2-eq/ha/year and reduce N_2O emissions by 10–20% (Lehmann and Joseph, 2015; Tao et al., 2024). Lehmann and Joseph (2015) emphasize the potential of biochar to enhance soil health and crop yields while reducing greenhouse gas emissions.

Integrated Pest Management (IPM): Implementing IPM strategies helps reduce the use of chemical pesticides and manage pest populations through biological control, cultural practices, and mechanical methods. This approach minimizes environmental

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contamination and promotes biodiversity. According to Pretty and Bharucha (2015), IPM can lead to sustainable pest management and improved crop productivity.

Water Recycling and Management: Efficient water use and recycling are vital for sustainable agriculture. Practices such as drip irrigation, rainwater harvesting, and wastewater treatment can help conserve water resources and reduce waste. According to Mpanga et al. (2022), innovations in water management, including soil health practices, irrigation methods, water harvesting, and precision agriculture, are essential for enhancing water use efficiency and sustainability in agriculture. Additionally, a study by Aivazidou et al. (2022) highlights the importance of integrating water management policies into sustainable institutional and corporate strategies to minimize freshwater consumption and pollution.

Waste-to-Energy Conversion: Utilizing agricultural waste to produce energy through biogas production or biomass combustion is an effective way to manage waste and generate renewable energy. This practice reduces reliance on fossil fuels and decreases greenhouse gas emissions. According to Kothari et al. (2010), biogas production from agricultural residues offers significant energy and environmental benefits.

Composting and utilization of biological waste

Composting is a valuable method for managing organic waste, transforming it into nutrient-rich soil amendments. This process enhances soil structure, fertility, and water retention, promoting sustainable crop production. Several key aspects and scientific findings underscore the importance of composting in agricultural waste management:

Microbial Activity and Decomposition: Composting relies on microbial activity to break down organic matter into humus. The process involves both aerobic and anaerobic microorganisms that decompose plant and animal residues. Insam and de Bertoldi (2007) emphasize that the efficiency of composting depends on factors such as temperature, moisture, pH, and the carbon-to-nitrogen ratio.

Types of Composting: There are various composting techniques including windrow composting, vermicomposting, and in-vessel composting. Each method has its advantages and is suited to different types of organic waste. Windrow composting, for example, is suitable for large-scale operations, whereas vermicomposting, which involves the use of earthworms, is ideal for smaller quantities of organic matter. Edwards et al. (2011) discuss the benefits and challenges of these composting methods.

Nutrient Enrichment: Composting enriches the compost with essential nutrients like nitrogen, phosphorus, and potassium, which are crucial for plant growth. A study by Bernal et al. (2009) highlights that composting not only recycles nutrients but also reduces the need for chemical fertilizers, thereby promoting sustainable agriculture.

Carbon Sequestration and Soil Health: Composting contributes to carbon sequestration by converting organic matter into stable humus, which is stored in the soil. This process helps mitigate climate change by reducing greenhouse gas emissions. Lehmann and Joseph (2015) illustrate that composting can enhance soil organic carbon content, improve soil structure, and increase water retention capacity.

Suppression of Plant Diseases: The heat generated during the composting process can destroy pathogens, weeds, and pests present in the organic waste. This results in a reduction of disease incidence when the compost is applied to crops. Hoitink and Fahy (1986) provide evidence that composting can effectively suppress soil-borne plant diseases.

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Environmental Benefits: Composting reduces the volume of waste sent to landfills and decreases methane emissions from anaerobic decomposition of organic matter in landfills. It also reduces the environmental impact of synthetic fertilizers and enhances soil biodiversity. A study by Epstein (2011) underscores the environmental benefits of composting, including the reduction of greenhouse gas emissions and improvement of soil health.

Use of sustainable packaging materials

The use of sustainable packaging materials in field crop farming is crucial for reducing the carbon footprint and promoting eco-friendly practices. Globally, agricultural packaging accounts for a significant portion of total packaging material use. According to a report by the Food and Agriculture Organization (FAO, 2013), agricultural packaging represents approximately 5% of the global packaging market, with a substantial portion attributed to field crops (FAO, 2013). Traditional packaging materials, such as plastic films and bags, contribute significantly to waste and greenhouse gas emissions. These materials can be replaced by biodegradable alternatives like cornstarch-based plastics, mycelium packaging, and recycled paper products, reducing environmental impact and supporting sustainable agriculture (Ibrahim et al., 2023).

The use of sustainable packaging materials in field crop farming is crucial for reducing the carbon footprint and promoting eco-friendly practices. Traditional packaging materials often contribute significantly to waste and greenhouse gas emissions. By adopting sustainable alternatives, farmers can minimize environmental impact and support sustainable agriculture.

Corrugated Cardboard: Made from renewable materials, corrugated cardboard is strong, durable, and easily recyclable. Its use in packaging can significantly reduce the environmental footprint by decreasing reliance on non-renewable resources and reducing waste (Silvestre et al., 2014; Ibrahim et al., 2023).

Kraft Paper: Another renewable and recyclable material, kraft paper is widely used for packaging. Its strength and biodegradability make it a popular choice for sustainable packaging, as it decomposes naturally and can be recycled multiple times (Selke et al., 2016).

Recycled Paper and Cardboard: Utilizing recycled paper and cardboard reduces the need for virgin materials and supports a circular economy. This practice helps decrease the overall environmental impact by minimizing resource extraction and reducing waste (González-García et al., 2009; Pfaltzgraff et al., 2013).

Mycelium Packaging: Derived from mushroom roots, mycelium packaging is an innovative and biodegradable alternative to traditional plastic packaging. It decomposes naturally, making it an excellent choice for reducing waste and supporting sustainable farming practices (Jones et al., 2020; Ibrahim et al., 2023).

Cornstarch Packaging: Made from renewable resources, cornstarch packaging is biodegradable and compostable. This material helps reduce the reliance on fossil fuels and decreases the environmental impact associated with conventional plastic packaging (Bastioli, 2001).

Bamboo Packaging: Bamboo is a fast-growing, renewable resource that can be used for various packaging needs. Its strength, durability, and biodegradability make it an ideal choice for sustainable packaging, supporting efforts to reduce waste in field crop farming (Scurlock et al., 2000; Ibrahim et al., 2023).

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Biodegradable Plastics: These plastics are designed to break down more quickly than traditional plastics, reducing their environmental impact. Made from plant-based materials, biodegradable plastics offer a sustainable alternative for packaging applications in agriculture (Hottle et al., 2013).

Technological innovations to reduce carbon footprint

Technological advancements play a crucial role in reducing carbon emissions and promoting sustainability. Here are some key innovations:

Implementation of smart agriculture and IoT

The implementation of smart agriculture and Internet of Things (IoT) technologies is revolutionizing the agricultural sector by enhancing productivity, sustainability, and resource efficiency. Smart agriculture integrates various IoT devices and systems to collect and analyze real-time data from the farming environment. This data-driven approach allows farmers to make informed decisions, optimize resource use, and reduce environmental impact, particularly in terms of carbon footprint (Friha et al., 2021).

IoT devices such as soil moisture sensors, weather stations, and crop health monitors provide continuous data on field conditions. This information helps farmers make timely interventions, reducing crop losses and improving yields (Friha et al., 2021). Precision irrigation systems use IoT sensors to measure soil moisture levels and deliver the right amount of water to crops, conserving water and ensuring optimal plant growth (Assimakopoulos et al., 2024). Smart agriculture and IoT technologies can reduce water usage by up to 30% through precision irrigation and decrease fertilizer application by 15-20% by optimizing nutrient delivery (Friha et al., 2021; Assimakopoulos et al., 2024).

IoT technology enables precise application of fertilizers and pesticides, reducing waste and environmental impact. Drones equipped with sensors can identify pest-infested areas and apply treatments only where needed, minimizing the use of chemicals and promoting healthier crops (Sethi and Sharma, 2023). IoT-based systems can detect early signs of plant diseases and pests, allowing for prompt action to prevent outbreaks, which minimizes the use of chemicals and promotes healthier crops (Friha et al., 2021).

Automated harvesting machines and robotic systems, guided by IoT data, optimize the harvesting process, reducing labor costs and improving efficiency. This automation reduces the carbon footprint associated with manual labor and enhances productivity (Villa-Henriksen et al., 2020). IoT technologies also enhance supply chain transparency by tracking produce from farm to table, ensuring food safety, reducing spoilage, and providing consumers with information about the origin and quality of their food (Wolfert et al., 2017).

The practice of big data analysis in agriculture further supports these advancements by providing deeper insights and predictive analytics, enhancing decision-making processes (Kamilaris et al., 2017). Additionally, digitalization of agricultural knowledge and advice networks promotes efficient information dissemination and collaboration among stakeholders (Fielke et al., 2020). An analytical survey on smart agriculture highlights the potential and challenges of integrating IoT technologies in farming (Yang et al., 2021).

Despite the numerous benefits, the implementation of smart agriculture and IoT faces challenges such as high initial costs, the need for technical expertise, and concerns about data privacy and security. Future research should focus on developing cost-effective solutions, improving user-friendly interfaces, and ensuring robust cybersecurity measures

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(Friha et al., 2021). Additionally, advancements in greenhouse automation and controlled environment agriculture can further support sustainable practices (Oliveira et al., 2016).

Role of drones and satellite imaging in farming

Technological advancements such as drones and satellite imaging have revolutionized modern agriculture, playing a crucial role in reducing the carbon footprint of field crop farming. These technologies offer precision, efficiency, and data-driven insights that traditional farming methods lack. Drones and satellite imaging enable farmers to optimize pesticide application, reducing usage by up to 25% while improving crop yields by approximately 5% (Zhang and Kovacs, 2012).

Drones: Unmanned aerial vehicles (UAVs), commonly known as drones, are extensively used in precision agriculture. They provide high-resolution images and real-time data that help farmers monitor crop health, manage irrigation, and detect pest infestations. By using drones, farmers can apply water, fertilizers, and pesticides more accurately, reducing waste and minimizing the environmental impact (Zhang and Kovacs, 2012; Turner et al., 2012). Recent advancements in drone technology have further enhanced their capabilities, allowing for more detailed analysis and better decision-making in farming practices (Karunathilake et al., 2023).

Satellite Imaging: Satellite imaging offers a broader perspective, allowing farmers to monitor large fields over time. This technology provides valuable information on soil conditions, crop growth, and weather patterns. Satellite imagery can be used to create detailed maps that guide planting and harvesting decisions, optimizing resource use and reducing the carbon footprint (Bastiaanssen et al., 2000; Beriaux et al., 2019). The integration of satellite data with machine learning algorithms has improved the accuracy of agricultural predictions and resource management (Qin and Chen, 2024).

Combining the data from drones and satellites enables farmers to make more informed decisions, improving efficiency and sustainability in field crop farming.

Utilizing artificial intelligence and big data for efficient farming

Artificial intelligence (AI) and big data have become essential tools in modern agriculture, significantly contributing to more efficient and sustainable farming practices. By leveraging these technologies, farmers can make more informed decisions, optimize resource usage, and reduce the carbon footprint of their operations.

Artificial Intelligence (AI): AI technologies such as machine learning algorithms and predictive analytics can analyze vast amounts of data to identify patterns and trends. These insights help farmers to predict crop yields, detect diseases early, and optimize planting schedules. AI-powered tools can also assist in precision farming by providing recommendations on irrigation, fertilization, and pest control, thereby reducing the use of water, chemicals, and energy (Kamilaris et al., 2017; Liakos et al., 2018). Recent advancements in drone technology have further enhanced their capabilities, allowing for more detailed analysis and better decision-making in farming practices (Chergui and Kechadi, 2022; Cavazza et al., 2023). AI and big data analytics can improve crop yield predictions by 10-15%, allowing for more efficient resource allocation and reducing waste by approximately 20% (Kamilaris et al., 2017; Liakos et al., 2018).

Big Data: The collection and analysis of big data in agriculture involve integrating data from various sources such as weather stations, satellites, drones, and sensors. This data provides a comprehensive view of the farming environment, including soil conditions, weather patterns, and crop health. By analyzing this data, farmers can make data-driven

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decisions that enhance productivity and sustainability. For example, big data analytics can identify the most effective crop varieties for specific soil types and climates, leading to higher yields and lower environmental impact (Mba et al., 2012; Razzaq et al., 2021). The integration of data from diverse sources allows for the development of predictive models that can forecast crop performance under varying environmental conditions (Kamilaris et al., 2017). This holistic approach helps in optimizing resource usage, improving yield predictions, and enhancing overall farm management (Wolfert et al., 2017; Liakos et al., 2018).

Combining AI and big data technologies enables farmers to adopt precision agriculture practices, which enhance efficiency, reduce resource wastage, and lower greenhouse gas emissions.

Practical strategies

Incentives and education programs for farmers

The effectiveness of practical strategies in reducing the carbon footprint is significantly enhanced when coupled with financial incentives and sustained education programs. Studies show that adoption rates of sustainable practices increase substantially when financial incentives are provided. For example, subsidies for precision agriculture equipment can increase adoption rates by 30-40%, while tax credits for implementing renewable energy systems can further incentivize farmers (Popp et al., 2014). Moreover, long-term profitability is enhanced when these practices are maintained through continuous education and technical support, ensuring that farmers are equipped with the knowledge and resources to sustain these practices over time (Lal et al., 2007). These combined approaches not only reduce environmental impact but also improve the economic viability of farming operations.

Financial Incentives: Governments and organizations can provide financial incentives such as subsidies, grants, and tax breaks to farmers who implement sustainable practices. These incentives can help offset the initial costs associated with transitioning to eco-friendly methods and technologies (Pretty and Bharucha, 2014). For example, subsidies for purchasing renewable energy systems or precision agriculture equipment can make these technologies more accessible to farmers (Popp et al., 2014).

Education and Training: Education programs are essential for disseminating knowledge about sustainable farming practices. Workshops, seminars, and online courses can help farmers stay updated on the latest research and techniques. These programs can cover topics such as soil health management, water conservation, and integrated pest management (IPM) (Lal et al., 2007). Extension services provided by agricultural universities and research institutions can also offer hands-on training and technical support to farmers (Danso-Abbeam et al., 2018; Abu Harb et al., 2024; Becerra-Encinales et al., 2024).

Addressing climate change requires coordinated efforts at both national and international levels. Various strategies can be employed to mitigate the carbon footprint of agriculture.

National Strategies: Countries can implement policies that promote sustainable agricultural practices. This includes setting regulations for carbon emissions, providing incentives for using renewable energy, and supporting research and development in sustainable farming (Smith et al., 2014). National governments can also invest in

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DOI: http://dx.doi.org/10.15666/aeer/2304_76417661

infrastructure projects that enhance water management and reduce soil erosion (FAO, 2017).

International Strategies: Global cooperation is essential for tackling climate change. International organizations such as the United Nations and the World Bank can facilitate knowledge exchange and provide funding for sustainable agriculture projects. Agreements like the Paris Agreement encourage countries to commit to reducing their carbon emissions and sharing best practices (United Nations, 2015).

Conclusion and future research directions

The integration of technological innovations in agriculture has shown significant potential in reducing the carbon footprint associated with field crop farming. Key findings from the review of current practices and research include:

Drones and Satellite Imaging: These technologies provide precise monitoring and management of agricultural fields, leading to more efficient use of resources and reduced environmental impact. By offering real-time data on crop health, soil conditions, and weather patterns, drones and satellite imaging enable farmers to make informed decisions that enhance productivity and sustainability (Bastiaanssen et al., 2000; Zhang and Kovacs, 2012; Turner et al., 2012; Beriaux et al., 2019).

Artificial Intelligence (AI) and Big Data: The application of AI and big data analytics in agriculture allows for the analysis of vast amounts of information from various sources. This integration helps in predicting crop yields, optimizing irrigation and fertilization, and detecting pests and diseases early. These data-driven insights lead to improved crop management practices, higher yields, and lower environmental impact (Mba et al., 2012; Kamilaris et al., 2017; Wolfert et al., 2017; Liakos et al., 2018; Razzaq et al., 2021).

Financial Incentives and Education Programs: Providing financial support and educational opportunities for farmers encourages the adoption of sustainable practices. Incentives such as subsidies and grants help offset the initial costs of new technologies, while education programs disseminate knowledge on best practices in sustainable farming. Extension services provided by agricultural universities and research institutions can also offer hands-on training and technical support to farmers (Lal et al., 2007; Popp et al., 2014; Danso-Abbeam et al., 2018; Pretty et al., 2018; Abu Harb et al., 2024; Becerra-Encinales et al., 2024).

National and International Strategies: Coordinated efforts at the national and international levels are crucial for mitigating the carbon footprint of agriculture. Policies that promote sustainable agricultural practices, along with global cooperation and funding, support the transition to more environmentally friendly farming methods (Smith et al., 2014; United Nations, 2015; FAO, 2017).

These findings highlight the importance of leveraging technological advancements and supportive policies to enhance the sustainability of agriculture. Future research should continue to explore innovative solutions and strategies to further reduce the environmental impact of farming.

Innovative approaches for further reducing carbon footprint

In the ongoing quest to mitigate the environmental impact of agriculture, several innovative approaches are emerging that promise to further reduce the carbon footprint. These approaches leverage advanced technologies and sustainable practices to create a more environmentally friendly agricultural system.

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DOI: http://dx.doi.org/10.15666/aeer/2304_76417661

1. Regenerative Agriculture: Regenerative agriculture focuses on revitalizing soil health and increasing biodiversity through practices such as cover cropping, crop rotation, and reduced tillage. This approach not only sequesters carbon in the soil but also enhances water retention and reduces the need for chemical inputs (Rhodes, 2017).
2. Carbon Farming: Carbon farming involves implementing practices that enhance carbon sequestration in agricultural lands. Techniques such as agroforestry, silvopasture, and biochar application can significantly increase the amount of carbon stored in soils and vegetation, thereby reducing atmospheric CO_2 levels (Paustian et al., 2016).
3. Precision Farming: Precision farming utilizes technologies like GPS, remote sensing, and IoT to optimize field-level management practices. By precisely applying water, fertilizers, and pesticides, farmers can minimize waste and reduce greenhouse gas emissions. This approach not only improves efficiency but also enhances crop yields and soil health (Zhang et al., 2002; Gebbers and Adamchuk, 2010).
4. Alternative Protein Sources: Shifting from traditional livestock farming to alternative protein sources such as plant-based proteins, insects, and lab-grown meat can drastically reduce the carbon footprint associated with food production. These alternative sources require fewer resources and produce significantly lower greenhouse gas emissions compared to conventional meat production (Tuomisto and Teixeira de Mattos, 2011; Godfray et al., 2018).
5. Renewable Energy Integration: Integrating renewable energy sources such as solar, wind, and biogas into farming operations can further reduce the carbon footprint. Renewable energy can power irrigation systems, machinery, and processing facilities, thereby reducing the reliance on fossil fuels and lowering greenhouse gas emissions (Nassar et al., 2019).
6. Circular Economy in Agriculture: Implementing circular economy principles in agriculture involves recycling waste products and repurposing them for other uses. For example, using crop residues for bioenergy production or animal feed can reduce waste and contribute to a more sustainable farming system. This approach minimizes resource input and promotes efficient use of agricultural by-products (Dey et al., 2022; Ali and Ali, 2023; Mulya et al., 2024).

Recommendations for future research

Despite significant progress in developing and implementing strategies to reduce the carbon footprint of field crop production, several knowledge gaps remain. These include: (1) the long-term effects and scalability of innovative mitigation strategies, especially in smallholder and resource-limited settings; (2) the socio-economic impacts and barriers to adoption of advanced technologies among diverse farming communities; (3) the integration and cumulative effects of multiple mitigation practices when applied together; and (4) the need for region-specific data on GHG emissions and mitigation potential for different crops and agro-ecological zones. Addressing these gaps will be essential for designing effective, context-specific policies and practices. To further enhance the sustainability of agriculture and effectively reduce its carbon footprint, future research should focus on the following key areas:

Integration of Emerging Technologies: Explore the potential of integrating other emerging technologies such as blockchain for supply chain transparency and Internet of

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DOI: http://dx.doi.org/10.15666/aeer/2304_76417661

Things (IoT) for real-time monitoring and automation. Research should aim to develop seamless systems that combine these technologies to optimize resource use and increase efficiency in farming practices (Kamilaris et al., 2017).

Development of Resilient Crop Varieties: Invest in genetic research to develop crop varieties that are more resilient to climate change and require fewer resources to thrive. Future studies should focus on identifying genes associated with drought tolerance, pest resistance, and other desirable traits to create crops that can withstand changing environmental conditions (Mba et al., 2012; Razzaq et al., 2021).

Sustainable Farming Practices: Investigate innovative farming practices such as vertical farming, agroforestry, and organic farming that can further reduce the environmental impact. Research should evaluate the long-term sustainability and scalability of these practices, as well as their potential to enhance biodiversity and soil health (Lal et al., 2007; Pretty et al., 2018).

Policy and Economic Incentives: Study the effectiveness of different policy and economic incentives in promoting the adoption of sustainable agricultural technologies among farmers. Research should analyze the impact of subsidies, grants, and tax incentives on farmer behavior and assess the cost-effectiveness of these measures (Popp et al., 2014).

Socio-Economic Impacts: Assess the socio-economic impacts of technological adoption in agriculture, particularly in developing countries, to ensure equitable benefits and address potential challenges. Future studies should examine how technological innovations affect smallholder farmers, labor markets, and rural communities, and develop strategies to support inclusive growth (Danso-Abbeam et al., 2018; Abu Harb et al., 2024; Becerra-Encinales et al., 2024).

By addressing these areas, researchers and policymakers can work together to develop comprehensive strategies that support sustainable agriculture and contribute to global efforts to mitigate climate change.

REFERENCES

[1] Abu Harb, S., Dayoub, M., Al-Najjar, K. (2024): The impact of agricultural extension program effectiveness on sustainable farming: A survey article. – International Journal of Agricultural Technology 20(2): 477-492.

[2] Aivazidou, E. (2022): Water Management in Agriculture and Industry: Challenges, Trends, and Opportunities. – Sustainability 14(1): 66. https://doi.org/10.3390/su14010066.

[3] Ali, J., Ali, T. (2023): Circular economy and agriculture: mapping scientific productivity, research pattern and future research direction. – Environment, Development and Sustainability 26: 30063-30108. https://doi.org/10.1007/s10668-023-03963-x.

[4] Assimakopoulos, F., Vassilakis, C., Margaris, D., Kotis, K., Spiliotopoulos, D. (2024): The Implementation of "Smart" Technologies in the Agricultural Sector: A Review. – Information 15(8): 466. https://doi.org/10.3390/info15080466.

[5] Baker, B. P., Green, T. A., Loker, A. J. (2020): Biological control and integrated pest management in organic and conventional systems. – Biological Control 140: 104095. https://doi.org/10.1016/j.biocontrol.2019.104095.

[6] Bastiaanssen, W. G. M., Molden, D. J., Makin, I. W. (2000): Remote sensing for irrigated agriculture: examples from research and possible applications. – Agricultural Water Management 46(2): 137-155. https://doi.org/10.1016/S0378-3774(00)00080-9.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2304_76417661

[7] Bastioli, C. (2001): Global status of the production of biobased packaging materials. – Starch-Stärke 53(8): 351-355. https://doi.org/10.1002/1521-379X(200108)53:8<351::AID-STAR351>3.0.CO;2-R.
[8] Becerra-Encinales, J. F., Bernal-Hernandez, P., Beltrán-Giraldo, J. A., Cooman, A. P., Cruz, J. C. (2024): Agricultural Extension for Adopting Technological Practices in Developing Countries: A Scoping Review of Barriers and Dimensions. – Sustainability 16(9): 3555. https://doi.org/10.3390/su16093555.
[9] Beriaux, B., Wynants, M., Lejeune, P. (2019): Contribution of Sentinel-2 satellite data to precision agriculture in Belgium. – Remote Sensing 11(18): 2134. https://doi.org/10.3390/rs11182134.
[10] Bernal, M. P., Alburquerque, J. A., Moral, R. (2009): Composting of animal manures and chemical criteria for compost maturity assessment. A review. – Bioresource Technology 100(22): 5444-5453. https://doi.org/10.1016/j.biortech.2008.11.027.
[11] Burney, J. A., Woltering, L., Burke, M., Naylor, R., Pasternak, D. (2010): Solar-powered drip irrigation enhances food security in the Sudano-Sahel. – Proceedings of the National Academy of Sciences 107(5): 1848-1853. https://doi.org/10.1073/pnas.0909678107.
[12] Cavazza, A., Dal Mas, F., Paoloni, P., Manzo, M. (2023): Artificial intelligence and new business models in agriculture: a structured literature review and future research agenda. – British Food Journal 125(13): 436-461. https://doi.org/10.1108/BFJ-02-2023-0132.
[13] Chergui, N., Kechadi, M. T. (2022): Data analytics for crop management: a big data view. – Journal of Big Data 9: 123. https://doi.org/10.1186/s40537-022-00668-2.
[14] Danso-Abbeam, G., Ehiakpor, D. S., Aidoo, R. (2018): Agricultural extension and its effects on farm productivity and income: insight from Northern Ghana. – Agriculture & Food Security 7(1): 74. https://doi.org/10.1186/s40066-018-0225-x.
[15] Dey, S., Pal, A., Nandy, A., Baishnab, K., Singh, P. K. (2022): Role of Circular Economy in Achieving Sustainable Growth in Agriculture and Food Sector. – Handbook of Sustainability Science in the Future 123(1): 1-19. https://doi.org/10.1007/978-3-030-68074-9_75-1.
[16] Edwards, C. A., Arancon, N. Q., Sherman, R. (2011): Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management. – CRC Press. ISBN 978-1-4398-0987-7, 623p. https://doi.org/10.1201/b10453.
[17] El-Ramady, H., Brevik, E. C., Bayoumi, Y., Shalaby, T. A., El-Mahrouk, M. E., Taha, N., Elbasiouny, H., Elbehiry, F., Amer, M., Abdalla, N., Prokisch, J., Solberg, S. Ø., Ling, W. (2022): An Overview of Agro-Waste Management in Light of the Water-Energy-Waste Nexus. – Sustainability 14(23): 15717. https://doi.org/10.3390/su142315717.
[18] Epstein, E. (2011): Industrial Composting: Environmental Engineering and Facilities Management. – CRC Press. ISBN 9780429106460, 340p. https://doi.org/10.1201/b10726.
[19] FAO. (2013): Sustainable Food Value Chains: Guiding Framework. – Food and Agriculture Organization of the United Nations. Retrieved from: http://www.fao.org/3/i3006e/i3006e.pdf.
[20] FAO. (2017): Water for Sustainable Food and Agriculture. – Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org.
[21] FAO. (2019): The State of Food and Agriculture. – Food and Agriculture Organization of the United Nations. www.fao.org.
[22] FAO. (2020). FAOSTAT: Food and Agriculture Data. – Food and Agriculture Organization of the United Nations. www.fao.org.
[23] Fielke, S., Taylor, B., Jakku, E. (2020): Digitalisation of Agricultural Knowledge and Advice Networks: A State-of-the-Art Review. – Agricultural Systems 180: 102763. https://doi.org/10.1016/j.agsy.2019.102763.
[24] Friha, O., Ferrag, M. A., Shu, L., Maglaras, L., Wang, X. (2021): Internet of Things for the Future of Smart Agriculture: A Comprehensive Survey of Emerging Technologies. – IEEE/CAA Journal of Automatica Sinica 8(4): 718-752. https://doi.org/10.1109/JAS.2021.1003925.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2304_76417661

[25] Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P. K., Toulmin, C., Vermeulen, S. J., Godfray, H. C. J. (2013): Sustainable intensification in agriculture: Premises and policies. – Science 341(6141): 33-34. https://doi.org/10.1126/science.1234485.
[26] Gebbers, R., Adamchuk, V. I. (2010): Precision agriculture and food security. – Science 327(5967): 828-831. https://doi.org/10.1126/science.1183899.
[27] Godfray, H. C. J., Aveyard, P., Garnett, T., Hall, J. W., Key, T. J., Lorimer, J., Scarborough, P., Springmann, M., Jebb, S. A. (2018): Meat consumption, health, and the environment. – Science 361(6399): eaam5324. https://doi.org/10.1126/science.aam5324.
[28] González-García, S., Berg, S., Feijoo, G., Moreira, M. T. (2009): Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. – The International Journal of Life Cycle Assessment 14(4): 340-353. https://doi.org/10.1007/s11367-009-0089-1.
[29] Han, X., Boota, M. W., Soomro, S., Ali, S., Soomro, S. G. H., Soomro, N. E., Soomro, M. H. A. A., Soomro, A. R., Batool, S., Bai, Y., Shi, X., Guo, J., Li, Y., Hu, C., Tayyab, M. (2024): Water strategies and management: current paths to sustainable water use. – Applied Water Science 14: 154. https://doi.org/10.1007/s13201-024-02214-2.
[30] Hasan, N., Pushpalatha, R., Manivasagam, V. S., Arlikatti, S., Cibin, R. (2023): Global Sustainable Water Management: A Systematic Qualitative Review. – Water Resources Management 37: 5255-5272. https://doi.org/10.1007/s11269-023-03604-y.
[31] Hillier, J., Hawes, C., Squire, G., Hilton, A., Wale, S., Smith, P. (2009): The carbon footprints of food crop production. – International Journal of Agricultural Sustainability 7(2): 107-118. https://doi.org/10.3763/ijas.2009.0419.
[32] Hoitink, H. A. J., Fahy, P. C. (1986): Basis for the control of soilborne plant pathogens with composts. – Annual Review of Phytopathology 24(1): 93-114. https://doi.org/10.1146/annurev.py.24.090186.000521.
[33] Holka, M. (2020): Assessment of carbon footprint and life cycle costs of winter wheat (*Triticum aestivum* L.) production in different soil tillage systems. – Applied Ecology and Environmental Research 18(4): 5841-5855. doi:10.15666/aeer/1804_58415855.
[34] Hollas, C. E., Rodrigues, H. C., Oyadomari, V. M. A., Agliardi, V. M., Bolsan, A. C., Venturin, B., Bonassa, G., Tápparo, D. C., Zonta, H. C. A., da Silva, J. F. F., Michelon, W., Cavaler, J. P., Antes, F. G., Steinmetz, R. L., Kunz, A. (2022): The potential of animal manure management pathways toward a circular economy: a bibliometric analysis. – Environmental Science and Pollution Research 29(23): 73599-73621. https://doi.org/10.1007/s11356-022-22799-y.
[35] Horowitz, J., Ebel, R., Ueda, K. (2010): "No-till" farming is a growing practice. – Economic Information Bulletin, 70. U.S. Department of Agriculture, Economic Research Service, 22p.
[36] Hottle, T. A., Bilec, M. M., Landis, A. E. (2013): Sustainability assessments of bio-based polymers. – Polymer Degradation and Stability 98(9): 1898-1907. https://doi.org/10.1016/j.polymdegradstab.2013.06.016.
[37] Ibrahim, I. D., Sadiku, E. R., Hamam, Y., Kupolati, W. K., Ndambuki, J. M., Snyman, J. (2023): Recent Recycling Innovations to Facilitate Sustainable Packaging Materials: A Review. – Recycling 8(6): 88. https://doi.org/10.3390/recycling8060088.
[38] Insam, H., de Bertoldi, M. (2007): Microbiology of the composting process. – In Waste Management Series 8: 25-48. Elsevier. https://doi.org/10.1016/S1478-7482(07)80006-6.
[39] IPCC. (2014): Climate Change 2014: Synthesis Report. – Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. World Meteorological Organization (WMO), Geneva, Switzerland. ISBN 978-92-9169-143-2, 151p.
[40] IPCC. (2019): Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and

greenhouse gas fluxes in terrestrial ecosystems. – Intergovernmental Panel on Climate Change. Retrieved June 9, 2025, from https://www.ipcc.ch/srccl/.
[41] Jensen, E. S., Peoples, M. B., Hauggaard-Nielsen, H. (2012): Faba bean in cropping systems. – Field Crops Research 115(3): 203-216. https://doi.org/10.1016/j.fcr.2009.10.008.
[42] Jensen, T. A., Antille, D. L., Tullberg, J. N. (2024): Improving On-farm Energy Use Efficiency by Optimizing Machinery Operations and Management: A Review. – Agricultural Research 14: 15-33. https://doi.org/10.1007/s40003-024-00824-5.
[43] Jones, M., Mautner, A., Luenco, S., Bismarck, A., John, S. (2020): Engineered mycelium composite construction materials from fungal biorefineries: A critical review. – Materials & Design 187: 108385. https://doi.org/10.1016/j.matdes.2019.108397.
[44] Kamilaris, A., Kartakoullis, A., Prenafeta-Boldú, F. X. (2017): A Review on the Practice of Big Data Analysis in Agriculture. – Computers and Electronics in Agriculture 143: 23-37. https://doi.org/10.1016/j.compag.2017.09.037.
[45] Karunathilake, E. M. B. M., Le, A. T., Heo, S., Chung, Y. S., Mansoor, S. (2023): The Path to Smart Farming: Innovations and Opportunities in Precision Agriculture. – Agriculture 13(8): 1593. https://doi.org/10.3390/agriculture13081593.
[46] Kothari, R., Tyagi, V. V., Pathak, A. (2010): Waste-to-energy: A way from renewable energy sources to sustainable development. – Renewable and Sustainable Energy Reviews 14(9): 3164-3170. https://doi.org/10.1016/j.rser.2010.05.005.
[47] Lal, R. (2004): Soil carbon sequestration impacts on global climate change and food security. – Science 304(5677): 1623-1627. https://doi.org/10.1126/science.1097396.
[48] Lal, R., Reicosky, D. C., Hanson, J. D. (2007): Evolution of the plow over 10,000 years and the rationale for no-till farming. – Soil and Tillage Research 93(1): 1-12. https://doi.org/10.1016/j.still.2006.11.004.
[49] Lantz, M., Svensson, M., Björnsson, L., Börjesson, P. (2007): The prospects for an expansion of biogas systems in Sweden-Incentives, barriers and potentials. – Energy Policy 35(3): 1830-1843. https://doi.org/10.1016/j.enpol.2006.05.017.
[50] Lehmann, J., Joseph, S. (2015): Biochar for Environmental Management: Science, Technology and Implementation. – Routledge. ISBN 9780203762264, 976p. https://doi.org/10.4324/9780203762264.
[51] Liakos, K. G., Busato, P., Moshou, D., Pearson, S., Bochtis, D. (2018): Machine learning in agriculture: A review. – Sensors 18(8): 2674. https://doi.org/10.3390/s18082674.
[52] Lobell, D. B., Schlenker, W., Costa-Roberts, J. (2011): Climate trends and global crop production since 1980. – Science 333(6042): 616-620. DOI: 10.1126/science.1204531.
[53] Mba, C., Guimaraes, E. P., Ghosh, K. (2012): Re-orienting crop improvement for the changing climatic conditions of the 21st century. – Agriculture & Food Security 1(7): 1-17. https://doi.org/10.1186/2048-7010-1-7.
[54] Mpanga, I. K., Gaikpa, D. S., Koomson, E., Dapaah, H. K. (2022): Innovations in Water Management: Agriculture. – In: Brinkmann, R. (ed.) The Palgrave Handbook of Global Sustainability. Springer, ISBN 978-3-031-01948-7, pp. 381-403. https://doi.org/10.1007/978-3-030-38948-2_33-1.
[55] Mulya, S. P., Hudalah, D., Salim, W., Prilandita, N. (2024): Review of the Circular Economy Implementation in the Agriculture Sector: A Regional Development Approach. – Circular Economy and Sustainability 5: 1509-1533. https://doi.org/10.1007/s43615-024-00463-6.
[56] Nair, P. K. R., Nair, V. D., Kumar, B. M., Showalter, J. M. (2010): Carbon sequestration in agroforestry systems. – Advances in Agronomy 108: 237-307. https://doi.org/10.1016/S0065-2113(10)08005-3.
[57] Nassar, N. T., Wilburn, D. R., Goonan, T. G. (2019): Renewable energy technologies and material supply chains. – Nature Sustainability 2(8): 759-766. https://doi.org/10.1038/s41893-019-0348-7.

[58] Nchu, F. (2024): Sustainable Biological Control of Pests: The Way Forward. – Applied Sciences 14(7): 2669. https://doi.org/10.3390/app14072669.
[59] Nelson, P. V. (2012): Greenhouse Operation and Management. – Prentice Hall, Published by Pearson. ISBN 978-0132439367, 624p.
[60] Olawepo, G. K., Kolawole, O. S., Isah, J. O. (2024): Enhancing Soil Carbon Sequestration in the Global South: The Roles of Microbes and Biological Matter. – In: Sustainable Soil Systems in Global South, Springer Nature Link, pp. 395-425. https://doi.org/10.1007/978-981-97-5276-8_14.
[61] Oliveira, J., Boaventura-Cunha, J., Moura Oliveira, P. (2016): Automation and Control in Greenhouses: State-of-the-Art and Future Trends. – In: Kozai, T., Fujiwara, K., Runkle, E. S. (eds.) Smart Plant Production: Greenhouse and Vertical Farming Technologies. Springer Singapore, pp. 597-606. https://doi.org/10.1007/978-3-319-43671-5_50.
[62] Pakhira, R., Singh, H. (2024): Enhancing Carbon Stocks in Agricultural and Forest Soils: A Crucial Step Toward Climate Change Mitigation and Ecological Security. – In: Warming Mountains, Springer Link, pp. 321-338. https://doi.org/10.1007/978-3-031-62197-0_16.
[63] Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., Smith, P. (2016): Climate-smart soils. – Nature 532(7597): 49-57. https://doi.org/10.1038/nature17174.
[64] Pfaltzgraff, L. A., De Bruyn, M., Cooper, E. C., Budarin, V., Clark, J. H. (2013): Food waste biomass: A resource for high-value chemicals. – Green Chemistry 15(2): 307-314. https://doi.org/10.1039/C2GC36978H.
[65] Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R. (2005): Environmental, energetic, and economic comparisons of organic and conventional farming systems. – BioScience 55(7): 573-582. https://doi.org/10.1641/0006-3568(2005)055[0573:EEAECO]2.0.CO;2.
[66] Popp, J., Lakner, Z., Harangi-Rákos, M., Fári, M. (2014): The effect of bioenergy expansion: Food, energy, and environment. – Renewable and Sustainable Energy Reviews 32: 559-578. https://doi.org/10.1016/j.rser.2014.01.056.
[67] Pretty, J., Bharucha, Z. P. (2014): Sustainable intensification in agricultural systems. – Annals of Botany 114(8): 1571-1596. https://doi.org/10.1093/aob/mcu205.
[68] Pretty, J., Bharucha, Z. P. (2015): Integrated pest management for sustainable intensification of agriculture in Asia and Africa. – Insects 6(1): 152-182. https://doi.org/10.3390/insects6010152.
[69] Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P. V. V., Reganold, J., Rockström, J., Smith, P., Thorne, P., Wratten, S. (2018): Global assessment of agricultural system redesign for sustainable intensification. – Nature Sustainability 1(8): 441-446. https://doi.org/10.1038/s41893-018-0114-0.
[70] Qin, S., Chen, H. (2024): Scientific and Technological Innovation Effects on High-Quality Agricultural Development: Spatial Boundaries and Mechanisms. – Agriculture 14(9): 1575. https://doi.org/10.3390/agriculture14091575.
[71] Razzaq, A., Kaur, P., Akhter, N., Wani, S. H., Saleem, F., Wani, F. (2021): Next-Generation Breeding Strategies for Climate-Ready Crops. – Frontiers in Plant Science 12: 620420. https://doi.org/10.3389/fpls.2021.620420.
[72] Rhodes, C. J. (2017): The imperative for regenerative agriculture. – Science Progress 100(1): 80-129. https://doi.org/10.3184/003685017X14876775256165.
[73] Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. A. M., Schmid, E., Stehfest, E., Yang, H., Jones, J. W. (2014): Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. – Proceedings of the National Academy of Sciences 111(9): 3268-3273. https://doi.org/10.1073/pnas.1222463110.
[74] Rout, P. R., Pandey, D. S., Haynes-Parry, M., Briggs, C., Cachicolo, H. L., Umapathi, R., Mukherjee, S., Goel, M. (2022): Sustainable Valorisation of Animal Manures via

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2304_76417661

Thermochemical Conversion Technologies: An Inclusive Review on Recent Trends. – Waste and Biomass Valorization 14(9): 553-582. https://doi.org/10.1007/s12649-022-01916-5.
[75] Scurlock, J. M. O., Dayton, D. C., Hames, B. (2000): Bamboo: An overlooked biomass resource? – Biomass and Bioenergy 19(4): 229-244. https://doi.org/10.1016/S0961-9534(00)00038-6.
[76] Selke, S. E. M., Culter, J. D., Hernandez, R. J. (2016): Plastics Packaging: Properties, Processing, Applications, and Regulations (3rd ed.). – Hanser Publications Munich. ISBN 978-3-446-40790-9, 467p.
[77] Sethi, S. S., Sharma, P. (2023): New Developments in the Implementation of IoT in Agriculture. – SN Computer Science 4: 503. https://doi.org/10.1007/s42979-023-01896-w.
[78] Silvestre, J. D., de Brito, J., Pinheiro, M. D. (2014): Environmental impacts and benefits of the end-of-life of building materials – calculation rules, results and contribution to a "cradle to cradle" life cycle. – Journal of Cleaner Production 66: 37-45. https://doi.org/10.1016/j.jclepro.2013.10.028.
[79] Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J. (2008): Greenhouse gas mitigation in agriculture. – Philosophical Transactions of the Royal Society B: Biological Sciences 363(1492): 789-813. https://doi.org/10.1098/rstb.2007.2184.
[80] Snyder, C. S., Bruulsema, T. W., Jensen, T. L., Fixen, P. E. (2009): Review of greenhouse gas emissions from crop production systems and fertilizer management effects. – Agriculture, Ecosystems & Environment 133(3-4): 247-266. https://doi.org/10.1016/j.agee.2009.04.021.
[81] Sørensen, B. (2004): Renewable Energy: Its Physics, Engineering, Environmental Impacts, Economics & Planning (3rd ed.). – Elsevier Academic Press. ISBN: 0-12-656153-2, 926p.
[82] Tao, F., Zhang, Z., Zhang, S., Rotter, R. P., Zhao, Z., Wang, Y. (2013): Climate change, wheat productivity and water use in the North China Plain: A new super-ensemble-based probabilistic projection. – Agricultural and Forest Meteorology 170: 146-165. https://doi.org/10.1016/j.agrformet.2011.10.003.
[83] Tao, Y., Feng, W., He, Z., Wang, B., Yang, F., Nafsun, A. I., Zhang, Y. (2024): Utilization of cotton byproduct-derived biochar: a review on soil remediation and carbon sequestration. – Environmental Sciences Europe 36: 79. https://doi.org/10.1186/s12302-024-00908-7.
[84] Tuomisto, H. L., Teixeira de Mattos, M. J. (2011): Environmental impacts of cultured meat production. – Environmental Science & Technology 45(14): 6117-6123. https://doi.org/10.1021/es200130u.
[85] Turner, D., Lucieer, A., Watson, C. (2012): An automated technique for generating georectified mosaics from ultra-high resolution UAV imagery, based on structure from motion (SfM) point clouds. – Remote Sensing 4(5): 1392-1410. https://doi.org/10.3390/rs4051392.
[86] United Nations. (2015): Paris Agreement. – United Nations Framework Convention on Climate Change. Retrieved from: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
[87] van der Werf, H. M. G., Petit, J. (2002): Evaluation of the environmental impact of agriculture at the farm level: A comparison and analysis of 12 indicator-based methods. – Agriculture, Ecosystems & Environment 93(1-3): 131-145. https://doi.org/10.1016/S0167-8809(01)00354-1.
[88] Villa-Henriksen, A., Edwards, G. T. C., Pesonen, L. A., Green, O., Sørensen, C. A. G. (2020): Internet of Things in arable farming: Implementation, applications, challenges and potential. – Biosystems Engineering 191: 60-84. https://doi.org/10.1016/j.biosystemseng.2019.12.013.

[89] Wang, Y., Akpa, F. A., Matthew, O., Ahsraf, J., Ogunbiyi, T., Osabohien, R. (2024): Maximizing environmental sustainability: Strategies for reducing carbon emissions and post-harvest losses. – Applied Ecology and Environmental Research 22(5): 4913-4930. doi:10.15666/aeer/2205_49134930.
[90] Wiedmann, T., Minx, J. (2007): A definition of carbon footprint. – ISAUK Research Report 07-01, 9p. United Kingdom.
[91] Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M. J. (2017): Big Data in smart farming – A review. – Agricultural Systems 153: 69-80. https://doi.org/10.1016/j.agsy.2017.01.023.
[92] World Bank. (2020): Agriculture and Food. – Retrieved from World Bank Agriculture and Food. https://www.worldbank.org/en/topic/agriculture.
[93] Yagi, K., Tsuruta, H., Kanda, K., Minami, K. (1996): Effect of water management on methane emission from a Japanese rice paddy field: Automated methane monitoring. – Global Biogeochemical Cycles 10(2): 255-267. https://doi.org/10.1029/96GB00517.
[94] Yang, X., Shu, L., Chen, J., Ferrag, M. A., Wu, J., Nurellari, E., Huang, K. (2021): A Survey on Smart Agriculture: Development Modes, Technologies, and Security and Privacy Challenges. – IEEE/CAA Journal of Automatica Sinica 8(2): 273-302. https://doi.org/10.1109/JAS.2020.1003536.
[95] Zhang, N., Wang, M., Wang, N. (2002): Precision agriculture a worldwide overview. – Computers and Electronics in Agriculture 36(2-3): 113-132. https://doi.org/10.1016/S0168-1699(02)00096-0.
[96] Zhang, C., Kovacs, J. M. (2012): The application of small unmanned aerial systems for precision agriculture: A review. – Precision Agriculture 13(6): 693-712. https://doi.org/10.1007/s11119-012-9274-5.
[97] Zhao, C., Qiu, R., Zhang, T., Luo, Y., Agathokleous, E. (2024): Effects of alternate wetting and drying irrigation on methane and nitrous oxide emissions from rice fields: A meta-analysis. – Global Change Biology 30(12): e17581. https://doi.org/10.1111/gcb.17581.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2304_76417661