Indian Journal of Information Sources and Services
ISSN: 2231-6094 (P) Vol.16, No.2, 2026, pp.692-703

DOI: https://doi.org/10.51983/ijiss-2026.16.2.69

Adoption of Technology for Sustainable Nitrogen Management in Agricultural Systems: A Review

Vivek Vishal Giri[1], Damodar Jena[2*], Bandana Nayak[3], Nishith Ranjan Parida[4], Itishree Panda[5] and Priyanka Mishra[6]

[1]KIIT School of Rural Management, KIIT Deemed to be University, Bhubaneswar, Odisha, India
[2*]KIIT School of Rural Management, KIIT Deemed to be University, Bhubaneswar, Odisha, India
[3]Faculty of Management Sciences, Siksha 'O' Anusandhan Deemed to be University, Bhubaneswar, Odisha, India
[4]KIIT School of Rural Management, KIIT Deemed to be University, Bhubaneswar, Odisha, India
[5]School of Sciences and Humanities, SR University, Warangal, Telangana, India
[6]KIIT School of Architecture and Planning, KIIT Deemed to be University, Bhubaneswar, Odisha, India
E-mail: [1]2281211@ksrm.ac.in, [2]damodarjena@ksrm.ac.in, [3]bandananayak@soa.ac.in, [4]nishith.parida@ksrm.ac.in, [5]itishree.panda@sru.edu.in, [6]priyanka.mishrafar@kiit.ac.in
ORCID: [1]https://orcid.org/0000-0003-1781-4679, [2]https://orcid.org/0000-0002-5107-7572, [3]https://orcid.org/0000-0002-6836-464X, [4]https://orcid.org/0000-0003-2066-3111, [5]https://orcid.org/0000-0003-4883-9107, [6]https://orcid.org/0009-0009-1235-7086
(Received 06 April 2026; Revised 09 May 2026, Accepted 19 May 2026; Available online 05 June 2026)

***Abstract* - Nitrogen (N) is a vital nutrient for plants, essential for photosynthesis, protein synthesis, and formation of nucleic acids, which stimulate plant growth and fruit development. Although application of nitrogen fertilizer has increased significantly since the Green Revolution, nitrogen use efficiency (NUE) has remained low at around 33%, indicating that almost two-thirds of applied nitrogen is lost to the environment. This leads to soil, air and water degradation, ultimately reducing agricultural productivity. The aim of this research is to determine the factors influencing the adoption of nitrogen management technologies in agriculture through a review of the existing literature. The research questions focus on identifying the major users of the N fertilizers, and examining whether the adoption is related to socio-economic conditions, educational background, landholding size, attitude of farmers, and environmental factors. It also explores the practices which enhance NUE and the attitudes that influence adoption of improved management practices that foster efficient use and minimize the extent of use of these fertilizers. The study screened 260 publications from the Scopus and Web of Science databases based on the PRISMA method, and reviewed 61 sources that met the criteria. This research contributes to SDG 12 and 13 and focuses on an integrated participatory approach. It emphasizes the role of individual characteristics in adoption of technology and recommends economically feasible and sustainable technologies supported by innovative financing mechanisms and government initiatives. The study highlights the importance of integrating user-friendly technologies and transformative agricultural services that will address the actual requirements of smallholder farmers. These measures will ensure food security while preserving ecosystems.**

***Keywords:* Nitrogen management, NUE (Nitrogen Use Efficiency), Sustainable Agriculture, Fertilizer Technology, Precision Agriculture**

I. INTRODUCTION

Nitrogen (N) is an essential component for all forms of life including people, animals, and plants since it contributes to plant productivity and carbon cycle. Nevertheless, agricultural efficiency of nitrogen is 35% (Singh, 2022). Excessive application of nitrogen-based fertilizers in crop production leads to diffuse pollution and excessive greenhouse gases emissions. Although this intensive usage was oriented at obtaining better agricultural outcomes, it has altered the natural cycle of nitrogen, which harms the biodiversity, human wellbeing, and water quality (Huang et al., 2015; Prakash et al., 2021; Sharma et al., 2024). There are a number of factors that influence the use of nitrogen fertilizers including geographical, socio-economic, demographic, ecological, and political, institutional and commercial (Pani et al., 2021; Prakash et al., 2021). Moreover, the nitrogen use efficiency (NUE) of the agriculture industry can also be determined by the relationships between the variables with the help of land area, economic index, global trade processes, livestock and crop regimes, and policy (Ali et al., 2025; Ren et al., 2022; Usman et al., 2022).

Green methods and agricultural technologies have played a major role in addressing various environmental challenges experienced around the world (Anderson et al., 2016; Xia et al., 2017). Sustainable agriculture may be described as those management practices that complement natural processes to conserve the natural resource base, reduce waste and environmental impact, and promote the resilience, self-regulation, evolution, and sustainable productivity of agro-ecosystems for common benefit (Das et al., 2025;

Velten et al., 2015). Sustainable practices and technologies may be highly beneficial in alleviating the environmental situation and this may include mitigating on unnecessary excessive reactive nitrogen pollution (Pretty, 2008). As an example, Denmark has been able to cut its agricultural surplus of nitrogen since the 1980s without affecting the agricultural production (Dalgaard et al., 2014). In its turn, the Netherlands minimized its surplus by up to 50 percent between 1992 and 2014 (Fraters et al., 2016). The majority of these enhancements were accomplished by supervising better management of the nitrogen flows in livestock systems and utilizing the organic and synthetic nutrients more efficiently in the production of crops. Despite the fact that there is still much to be desired, better nitrogen management has proved to be quite useful to society (Krishnamoorthy & Rajiv, 2017; Van Grinsven et al., 2016).

Several studies highlight a decline in the application of manure, linked to limited awareness of fertilizer management and its role in controlling unintended environmental impacts (Aryal et al., 2021). The practice of adopting crops, soils, and water management techniques and practices are not very extensive, despite efforts towards promoting sustainable management (Olum et al., 2020). As a matter of fact, simple presence hardly assists in the adoption of technology. This is because the diffusion process usually involves a range of factors, including financial position, environmental, market, and regulatory environment, at the level of the farmer (Azam & Shaheen, 2019). More to the point, attitudes towards a practice on a personal level, social contexts, and perceived relative advantages of a practice over current ones play a decisive role in the process of adoption (Aryal et al., 2020).

A growing body of literature addresses the adoption of sustainable farm management practices, with a comprehensive overview provided by Piñeiro et al., (2020). However, few studies have investigated the specific drivers and barriers affecting the adoption of sustainable nitrogen management technologies.

This paper seeks to answer the following questions through the PRISMA method, using an extensive review of publications indexed in Scopus and Web of Science databases: (i) who are the major users of N fertilizers, (ii) what key factors influence the adoption, including socio-economic status, level of education, size of landholdings, farmer perceptions and attitude, and environmental conditions; and (iii) what type of practices improve NUE?

Key Contribution

1. The study provides a comprehensive synthesis of 61 articles, offering an up-to-date overview of technologies and practices for sustainable nitrogen management in agriculture.

2. It develops a structured framework of adoption determinants, systematically organizing drivers and barriers into economic, social, technical, institutional, demographic, and environmental categories.

3. It advances policy and practice by advocating integrated, participatory, and long-term strategies that connect user-friendly technologies, innovative financing, and supportive governance with improved NUE and the achievement of SDGs 12 and 13.

The paper is structured as follows: Section II describes a PRISMA-based systematic review of Scopus and Web of Science that narrows 260 records to 61 studies. Section III reports the geographic and temporal distribution of studies, key drivers and barriers to technology adoption, and major nitrogen management techniques and practices. A brief research gaps section highlights missing work on farmer decision-making, integrated technology packages, predictive models, and participatory approaches. Section IV links findings to extension, social learning, incentives, technology design, and long-term regulation, and the section V calls for integrated, participatory, multi-dimensional strategies to improve NUE and protect ecosystems

II. Materials and Methods

The PRISMA technique has been used in this review paper. Fig. 1 illustrates the key steps followed in this study to systematically obtain the relevant research articles. In the first stage, a search was conducted using the Scopus and Web of Science databases. The search was performed using a set of keywords, viz., *“management,” “nitrogen,” “technology,” “adoption,” “farmers,” “crops,” “sustainability,” and “agriculture”.

A. Literature Selection Criteria

The research paper used specific evaluation criteria to identify relevant studies that fulfilled following research objectives: to establishment of the relationship between socio-economic characteristics of marginal and small holder farmers and nitrogen fertilizer use; identify the types of practices and technologies adopted by marginal and smallholder farmers to increase NUE; and evaluating the cost effectiveness of the nitrogen management practices that aimed at reducing the use of nitrogen fertilizer.

Relevant literature related to the above objectives such as journal articles, conference papers, and working papers were downloaded and filtered in terms of their titles and abstracts. The articles that were not meeting the specified purposes were filtered out.

Web of science and Scopus databases were selected to download 260 documents. Based on this, 25 duplicate documents were eliminated in the initial search results. The documents that were included in the literature synthesis were screened in terms of abstract and 174 documents were filtered out based on criteria of not addressing the objectives of the review or for not discussing practices and techniques that used nitrogen. Finally, 61 documents were reviewed as shown in fig. 1.

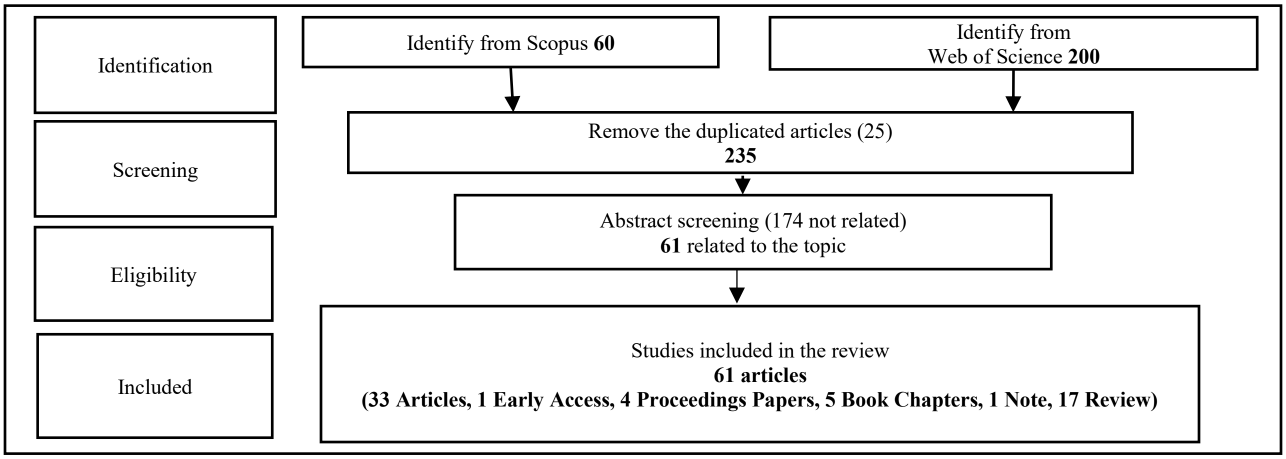

Fig. 1 PRISMA Flow Diagram Showing the Steps Involved in the Systematic Review

III. RESULTS

Table I shows the geographical distribution of literature, which showed that China ranked the highest at 19.67 %, followed by India (9.84 %) and African countries (8.20 %).

Fig. 2 displays documents per year published (1993-2025), with a larger percentage (70 %) of studies published in the past ten years, indicating an increased research interest in recent years.

TABLE I GEOGRAPHY-WISE CLASSIFICATION OF STUDIES

Geography	No. of Studies	Percentage (%)
China	12	19.67
General / Global (Reviews & Meta-Analyses)	11	18.03
India	6	9.84
Africa (Regional or Multi-Country)	5	8.20
United States	4	6.56
South Asia (Regional)	3	4.92
Europe (Regional)	2	3.28
Sub-Saharan Africa (Regional)	2	3.28
Canada	1	1.64
Côte d'Ivoire	1	1.64
Myanmar	1	1.64
Senegal	1	1.64
Sri Lanka	1	1.64
Sudan	1	1.64
Tropics (Regional)	1	1.64
Uganda	1	1.64
Not Specified / Model-Based	8	13.11
Total	61	100.00

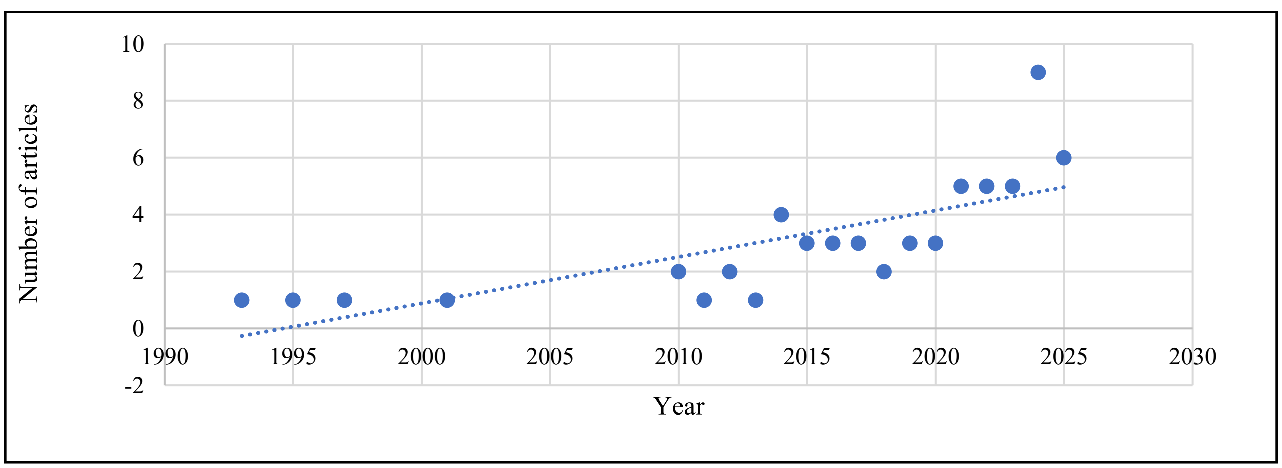

Fig. 2 Number of Articles Per Year

A. *Driving Factors and Barriers of Agricultural Technology Adoption*

The research found two important findings: first, the use of agricultural technologies was low among the small and marginal farmers; and second, there is a need to better comprehend the general factors that motivate farmers to adopt agricultural technologies in the various research situations.

The studies evaluated mainly focused on certain aspects such as various technologies, conservation agriculture, organic fertilization, precision irrigation, and nitrogen management. The main factors were the economic, social, technical, and environmental variables noted in the studies. Overall, the studies were linked to productivity, efficiency, profitability, and sustainable environmental management.

In order to outline the most significant findings of the studies, the following key factors were identified for the adoption of agriculture technologies: agricultural extension and training were critical in acquiring and raising awareness among farmers (Huang et al., 2015; Pan et al., 2017; Wood et al., 2022) economic factors, including income level and access to credit, provided farmers with the capacity to implement the new technologies (Begho et al., 2022; Olum et al., 2020; Piñeiro et al., 2020).

In addition, the studies also mentioned some of the outstanding technologies specifically, the use of sensors for nitrogen management, precision fertilization, slow-release fertilizers, and organic farming and cover crops to improve soil fertility and reduce the reliance on nitrogen fertilizer. Biological technologies were also mentioned such as beneficial microbes and nitrogen-fixing legumes. Obstacles observed in literature comprised of high cost of new technologies, lack of knowledge and technological assistance, low trust or belief of the benefits or reliability of the practices by farmers and risk in the absence of guaranteed pay-off.

The studies highlighted different dimensions and outcomes of technology adoption across clients and/or regions. In Africa, the focus was on soil fertility improvement and low-cost technologies. In Asia, the emphasis and outcomes were related to nitrogen management and irrigation efficiency. In Europe and the Americas, the research focused mainly on precision agriculture and smart farming technologies.

B. *Techniques and Practices*

As shown in fig. 2, a number of methods were found to be applicable for soil nitrogen management in the 61 articles that were reviewed. Digital methods were found to be the most common, constituting 34.43%, which encompassed decision support systems, soil sensing systems, artificial intelligence, and precision agriculture software (Liu et al., 2023; Liu et al., 2025; Papadopoulos et al., 2011; Viscarra Rossel & Bouma, 2016). The second most prevalent was integrated management practices (18.03%) and concentrated on site-specific nutrient management and agronomic systems integration (Peng et al., 2010; Wu et al., 2021; Xia et al., 2017). Likewise, farmer-controlled input regulation methods also constituted 18.03%, with a focus on behavioral change and knowledge-based nitrogen management (Hamid et al., 2021; Wood et al., 2022). Training-based adoption strategies also made up 13.11% (Huang et al., 2015; Pan et al., 2017). The application of inhibitors was less common, constituting 8.20% (Cantarella et al., 2018; Coskun et al., 2017), as well as incentive-based strategies, which also constituted 8.20% (Geussens et al., 2019; Piñeiro et al., 2020).

1) **Training and Education-Based Adoption:** This method is largely founded on a well-established mechanism of educational programs to make farmers aware of nutrient-related issues and possible solutions (Shortle et al., 2020). This often occurs in and throughout on-farm workshops and field days, the primary goal being farmers learning about the importance of applying nitrogen fertilizers at the right rate, which is enough for crops but not enough to negatively impact yield or productivity. This knowledge also improves economic efficiency while increasing revenue for farmers.

2) **Advanced Technologies:** This is the most technologically complex approach, where contemporary methods are applied to oversee crop needs and manage resources with high precision. This also has many subcategories:

   - **Remote Sensing:** A network of satellites, along with WorldView-3 data, is being utilized to determine the crop health and vitality (Arizo-García et al., 2025; Sibanda et al., 2017).

   - **Ground-Based Sensors:** Ground-based sensors measure nitrogen loss to improve crop fertilizer management strategies. Ground-based sensors enable continuous monitoring of soil nitrogen levels (Papadopoulos et al., 2011; Peng et al., 2010).

   - **Computer Modelling:** Computer modelling and Decision Support Systems (DSS) are employed to improve nitrogen application rates in each region of agriculture (Papadopoulos et al., 2011; Peng et al., 2010; Shu et al., 2025).

   - **Constructed Wetlands:** This is an engineering remedy designed to address accumulation of nutrients in soils and promotes denitrification of surplus nitrogen in drainage water to ensure nutrients remain in the field in response to the demand of plants besides reducing nitrogen load by approximately 52% through 2 central ways namely controlled drainage and bioreactors. Controlled drainage is accomplished through the use of managed tile drainage systems that keep drainage water within the soil. Bioreactors are a novel approach that uses deep, subterranean trenches filled with a carbon source to convert nitrate in drainage water to nitrogen gas, reducing excess nitrogen from the soil (Christianson et al., 2014; Negi et al., 2022).

- **Variable Rate Technology (VRT):** This technology uses plant sensing to calculate crops' precise nitrogen requirements, which increases profitability by cutting nitrogen prices or increasing grain yield (Boyer et al., 2011).

- **Calibration:** Simulation-based calibration could identify optimal crop species and planting time using temperature monitoring and comparing it with planting history (Kheir et al., 2021; Xiong et al., 2014). These methods seek "precision customisation" to improve NUE while minimising losses and environmental damage. The primary problems with technology are high initial costs and technical complexity, which prevent smallholder farmers from widespread adoption.

3) **Nitrogen inhibitors and stabilized fertilizers:** This strategy would help to enhance the effectiveness of nitrogen fertilizers instead of altering the rate or method of fertilizer application. This involves a number of strategies:

- **Soil Acidification with Sulphuric Acid Solution:** Appropriate agronomic measures can enhance the uptake of nitrogen by plants. The acidification of the soil using sulfuric acid and the reduction of the soil pH will allow stabilizing the ammonium nitrogen rather than letting it turn into ammonia gas. Therefore, applying sulfuric acid will decrease the pH or alkalinity of the soil (Nie et al., 2012).

- **Urease Inhibitors:** Urease inhibitors are a practical way to reduce the losses of ammonia. These compounds slow the hydrolysis of urea to ammonia and reduce the loss of nitrogen into the atmosphere as ammonia gas. For example, including NBPT in urea has been demonstrated to reduce ammonia losses of urea by about 53% (Cantarella et al., 2018).

- **Nitrification Inhibitors:** Biological nitrification inhibitors (BNIs) can slow the conversion of ammonium to nitrate via compounds that are exuded by the roots of some plants, thereby reducing nitrogen leaching to both groundwater and emission of nitrous oxide (N_2O) in soils (Coskun et al., 2017).

These products are sometimes advertised as ready-to-use products blended with fertilizer; they are often called "stabilized urea". This approach is cheap and relatively straightforward for producers to adopt and requires no changes in their existing equipment and no changes in core farming practices.

4) **Organic and integrated nutrient management:** This strategy is rooted in a broader sustainability philosophy since it is not exclusively reliant on chemical fertilizers, but incorporates them with a variety of natural and improved nutrient sources, which include:

- **Utilizing Green Manure**: The incorporation of green manure (legume residues) contributes to nitrogen supply, and the nitrogen use efficiency is virtually identical under rainfed and irrigated conditions. Therefore, it has been stated that nitrogen sources in green manure are frequently more effective than mineral or synthetic nitrogen fertilizers under non-rainfed low conditions (Becker et al., 1995).

- **Utilizing Organic Fertilizers**: Replacing conventional farming with organic agriculture has influenced profit margins and labor requirements favorably, and also decreases nitrogen imports. The degree to which organic farming enhances local patterns of crop and livestock production and demands specialized policies and payment to organic farming to achieve environmentally sustainable agricultural management (Timlin et al., 2024; Wang et al., 2024; Wittmann et al., 2024).

- **Minimized Tillage:** Although tillage may be required to mineralize an adequate level of nitrogen or to create an appropriate seedbed, it can decrease the content of the soil organic matter overtime, augment greenhouse gas emissions, and raise the vulnerability of soil erosion (Lundy et al., 2015; So et al., 2001; Verhulst et al., 2011).

- **Crop Rotation with Legumes:** The process of agricultural intensification depletes nutrients from the soil, leading to lower yields of crops. On the other side, a crop rotation with legumes helps provide nutrition through nitrogen without the additional dependence on externally supplied nutrients, such as fertilizers. It can save time and money of farmers and enable them to engage in other agricultural activities (Castro-Rincon et al., 2018; Craswell et al., 1997).

- **Biological Control:** It utilises living organisms like Rhizobia that are able to colonise the roots of the plants and form symbiotic relations with the leguminous plants through biological nitrogen fixation (Adeleke et al., 2019; Das et al., 2017). This integrated strategy combines traditional and modern methods to increase long-term soil fertility, improve soil health, and reduce reliance on external inputs. Its success is dependent on both the availability of organic inputs and the use of local knowledge.

5) **Policy and Incentive-Based Adoption:** In this method, governments or regulatory organisations can stimulate adoption by issuing regulations that provide economic signals, such as:

- **Regulatory Measures (Taxes or Fees):** Policy mechanisms can be employed to limit or reduce pollution of the environment due to excessive nitrogen fertilizer use. To illustrate; the Everglades Forever Act of 1994 which was passed in the U.S. obliges farmers to obtain permits to comply with the environmental conservation practices. In these instances, the preferred approach is voluntary, while regulations are only enforced if necessary. This can be said to provide a complementary approach, placing the state in a legal position of responsibility to reduce agricultural pollution (Shortle et al., 2020).

- **Financial subsidies and payments for ecosystem services:** Incentives can also be based on agriculture and soil measures that reward farmers for using optimal fertilizer rates and practices that provide ecosystem services, as well as soil and product quality improvements. Payment for ecosystem services will also cover the costs of acquiring and using tools such as remote sensing equipment and nitrification inhibitors, which can reduce the environmental impacts of agricultural practices (Geussens et al., 2019).

6) **Farmer-led adoption or participatory adoption:** In this mode, farmers are central in developing and spreading technology. Rather than imposing a solution top-down, this model emphasizes:

- **Participatory Learning:** Farmers conduct tests of technologies themselves using on-farm trials (Wood et al., 2022).

- **Local Adaptation:** Farmers also adapt the proposed technologies to meet local conditions, resources, and state of knowledge (Macdonald et al., 2018).

- **Social Networks:** Peer-to-Peer sharing stimulates the exchange and sharing between neighbours or groups of farmers on emerging practices (Skaalsveen et al., 2020).

This model stresses the importance of flexibility and adaptation of technologies in the adoption process, using an orientation of a learning journey rather than technology transfer. Therefore, this learning journey is more likely to lead to stable and sustained adoption, because the process is grounded in farmers' real needs and constraints (Fig. 3).

Fig. 3 Word Cloud Showing the Frequency of Technology Adoption of Nitrogen Management

7) **Cost factors affecting adoption:** Many factors influence the adoption of appropriate nitrogen management technologies for soils, some of which are related to the characteristics of farmers or their personal relationships with demographic or economic aspects of their lives, and others are related to social, institutional, or environmental influences.

Overall, factors influencing the successful adoption of nitrogen management technologies fall into combinations of these factors to maximize higher productivity or lower costs of production, as well as the supportive roles of public policy or agricultural extension services in this process, as shown in table II.

Factors affecting the adoption of nitrogen management technologies fall under the following broad categories:

- **Demographic Characteristics:** Demographic characteristics, including the farmers' age, education level, and gender, play a significant role in the adoption of agricultural practices. Younger farmers often adopt new practices faster than older farmers because adoption is sometimes associated with how a farmer perceives technology as useful or practicable. Education levels facilitate adoption since more educated farmers are better able to adopt modern technology than illiterate farmers, who may not have the capacity to adopt these practices. Economic status also plays an important role in adoption since high initial costs can be a limiting factor and an obstacle, especially for smallholder farmers. However, high economic benefits from agriculture are important and influential factors of adoption. Thus, opening channels through which farmers can access loans from local banks and offering government subsidies are measures that empower farmers and increase their opportunities to engage in the adoption of new technologies.

- **External Factors:** These factors include technical factors that pertain to nitrogen management technologies, such as operational and maintenance characteristics. As with a limited understanding of these procedures, a lack of understanding of the technologies' importance and their advantages can also impede the spread of the technologies (Mishra et al., 2024). Several studies have suggested that knowledge infrastructure must be developed for the effective application of remote sensing devices, precision irrigation systems, and subsurface drainage systems. Such knowledge infrastructures are a key precondition for the technologies to be both feasible and effective in nitrogen management.

- **Institutional, Governmental, and International Support:** These are the one of the most important ways through which farmers access to new technologies. Several key government policies include financial subsidies, tax breaks, and regulation of the environment. In addition to these policies, government-led marketing avenues for nitrogenous and bio-fertilizers, as well as seed with desired genetic traits, are hugely important for providing farmers with these inputs. Availability of reasonable price inputs becomes a key factor in promoting adoption.

- **Environmental Factors and Local Conditions:** The main environmental factors affecting optimal nitrogen uptake by plants include soil texture, pH, organic matter, water availability, rainfall, and temperature, all of which significantly influence the effectiveness of nitrogen-interacting technologies (Pani et al., 2020; Prakash et al., 2022). Finally, research has shown that crop responsiveness to the integrative management of nitrogen varies both among and within crop species based on their genetic composition.

TABLE II FACTORS INFLUENCING THE ADOPTION OF SOIL NITROGEN MANAGEMENT TECHNOLOGIES

Main Factor	Sub-Factor	Supporting Articles
1. Economic and Financial Factors	High initial financial cost; economic return and profitability	(Dsouza & Mishra, 2016; Sheng et al., 2021)
2. External Factors	Technical complexity and difficulty of use	(Begho et al., 2022; Y. Liu et al., 2025)
	Lack of knowledge and technical skills	(Narwal, 2006)
	Access to infrastructure, including drainage and nitrogen removal systems	(Y. Liu et al., 2025)
	Access to inputs (improved seeds, bio-fertilizers)	(Gnahoua et al., 2016; Solomon, 2010)
3. Demographic Attributes	Demographic characteristics (age, education), agricultural holding features (size, type), social networks, and learning from others	(Bhattacharyya et al., 2023; Munz & Schuele, 2022)
	Beliefs and perceptions (perceived benefits, ease of use), risk, and uncertainty	(Hamid et al., 2021)
4. Institutional, Governmental, and International Support	Access to credit and financing and government support and subsidies, quality and efficiency of agricultural extension services, governmental policies and regulations, marketing channels, and access to inputs	(Dsouza & Mishra, 2016; Martínez-Dalmau et al., 2021)
	Marketing channels and access to inputs	(Gallardo et al., 2020)
	Joining cooperatives	(Amadu et al., 2021; G. Wei et al., 2022)
5. Environmental and Local Conditions	Soil characteristics (fertility, texture, pH)	(Bhattacharyya et al., 2023; Wu et al., 2021)
	Climatic conditions and water availability	(Bhattacharyya et al., 2023; Pan et al., 2017; S. Wei et al., 2024)
	Crop type and response to technology	(Bhattacharyya et al., 2023; Mermut, 2012)
	Environmental stresses (e.g., degradation)	(Bhattacharyya et al., 2023; S. Wei et al., 2024)

C. Key Findings from the Studies

The reviewed studies indicate that the adoption of nitrogen management technologies among small and marginal farmers is still low, despite the extensive availability of innovations; the adoption decisions are influenced by a combination of economic, social, technical, institutional, demographic, and environmental aspects, and among the widely used practices were the digital tools (including decision support systems, soil sensing technologies, artificial intelligence, and precision agriculture software), along with integrated approaches to nitrogen management, and farmer-led knowledge-based approaches. In addition, policy incentives, participatory learning, extension services, and training programs were identified as critical drivers in improving nitrogen use efficiency (NUE) and promoting sustainable agricultural practices.

D. Research Gaps

A critical review of the existing literature has identified various key research gaps, the most significant of which are: the literature is focused to be not enough on farmers' decision-making processes and comparative analyses on the effectiveness of adopting integrated technology packages; the lack of strong predictive models that incorporate future climate change scenarios, price variability, and their implications on the long-term feasibility of adopting these technologies; most studies on sustainable agricultural practices are concentrated in European countries. Moreover, no comprehensive frameworks have been established to classify the stages that farmers go through to adopt nitrogen management technologies, from intention to full adoption, and ultimately continued use, beyond the simplistic binary understanding of farmers' decisions ("yes" or "no"); pre- and post-adoption phases of nitrogen management technologies have not been adequately compared in many studies, nor has the long-term sustainability of farmers' continued reliance on those practices been examined; the precise measurement of certain intermediary influencing variables, such as age and gender, remains challenging, despite their established effects in several studies. This is because of individual differences and varying levels of awareness even within similar age or gender groups, highlighting the need for comparative measures within similar demographic categories; finally, there is a marked shortage of applied studies using fully participatory methodologies that involve farmers at all stages of technology development and transfer to ensure that innovations meet the real conditions and immediate needs of farmers.

IV. DISCUSSION

The review of 61 documents studies provides several key lessons that could help deal with nitrogen pollution-related issues and, at least partly, contribute to attaining the Sustainable Development Goals, namely SDG 13 (climate action) and SDG 12 (responsible consumption and production). Among others, the following strategies, as derived from the reviewed literature, are most relevant:

- Measuring the total yield gap and the exploitable yield gap by crop models, diagnostic surveys of smallholders, and controlled comparative experiments helps to pinpoint the main factors influencing nitrogen fertilization frequency (Wang et al., 2023). Access to information through agricultural extension and training programs is one of the most influential drivers that enables farmers to adopt sustainable agricultural technologies, which optimize nitrogen use. This can be fostered by continuous learning processes of the stakeholders and by collaboration between governmental and non-governmental organizations with the purpose of information exchange, for example, through agricultural cooperatives providing frequent peer training for farmers.
- This involves integrating education and training into existing programs, with support for farmers to ensure they can take advantage of the programs. Consideration should also be given to access, credibility, and relevance of information throughout the dissemination process. Farmers must receive information exactly at the time it is most effective in bringing about adoption. In addition, awareness of the sources of nitrogen "leakages" and sufficient farmer-level training on any new or improved nitrogen management innovation are needed. Tying information exchange to social networks also has a great deal of potential.
- It may be possible to incorporate the opinion of farmers when identifying yield-limiting factors using PRA since most of the small-scale farmers in India have no access to such resources. Accordingly, Begho et al., (2022) suggest that the farmers should then liaise with field researchers in undertaking quantitative analysis of such aspects.
- Among these, one that comes to the fore is the integrated and participatory management approach, in which flexible and locally adapted technology packages are developed for every farmer and region in place of one-size-fits-all solutions. This necessitates the need for reinforcing the role of transformative agricultural extension beyond the provision of information to a mediating and facilitating role informed by deep insights into the behavioural and social barriers of farmers, such as perceived risk, complexity, and mistrust of potential returns.
- The economic key lesson, therefore, is that financial viability is the driver. Recommendations need, hence, to focus on making sustainable technologies directly attractive from an economic point of view. This encompasses not just providing subsidies for inputs such as, biofertilizers or sensors, but also devising novel financing methods, like tying reduced-interest borrowings to enhanced input efficiency, and establishing marketplaces for "low-carbon" or "sustainably grown" farm goods that allow producers the advantage of receiving higher rates. Moreover, the plans for shared equipment and expertise, such as precision farming aid provided by expert contractors, prove useful in bypassing the initial steep outlay hurdles encountered by smaller farmers. Cooperation between authorities and the commercial sector ought to drive the funding and broader adoption of these systems.
- From this perspective, a core understanding is that the acceptance of new technological developments will, to a large extent, depend on how convenient and useful they are to use. "Intuitive" goods and services that do

not require excessive abilities and effort from growers ought to be the focus toward which technical progress should move. Funding for the investigation and creation of digital systems that employ handheld devices for field-specific nutrition advice or the design of affordable and dependable sensors is certain to yield great returns. Furthermore, the investigation ought to pivot from examining isolated technology effects to studying the outcomes of technology suites, such as merging organic fertilizers with adjusted mineral amounts and water-conserving methods, so that assessing mutual financial and ecological advantages can be accomplished accurately.

- In practical terms, the findings highlight important implications for information management and digital advisory services in agriculture. The prominence of digital nitrogen management tools (decision support systems, soil sensing platforms, and AI-based applications) shows that well-designed information systems can translate complex agronomic knowledge into field-level decisions for smallholders. At the same time, the central role of agricultural extension, training, and social networks underlines that digital libraries and information services must provide timely, context-specific, and credible content, ideally integrated with local extension channels, to effectively support technology adoption and improved nitrogen stewardship
- The necessity of long-lasting, coordinated, and authorizing regulations is the final but crucial lesson. Only short-term trial initiatives would be able to bring about fundamental changes. Long-term strategic frameworks that integrate nutrient handling objectives with a broader range of policies related to food security, climate adaptation, and water resource conservation must be established by administrations. This requires comprehensive environmental legislation supported by incentive-based mechanisms that encourage the adoption of best management practices, along with continuous investment in capacity building at all levels, including growers, extension personnel, and policymakers. In other words, the transition to more environmentally friendly farming practices for nitrogen stewardship is not a choice; rather, it is necessary.

The findings emphasize the importance of a people-and-nature-aligned approach, which creates conditions for growers to collaborate meaningfully in the process of transformation. Through an integrated, human-centered approach that recognizes the complexity of growers' decisions and supports them economically, technically, and socially, the world would witness efficient and long-lasting food production systems, a cleaner environment, and more resilient rural communities capable of withstanding future challenges.

V. Conclusion

The agriculture is struggling to manage nitrogen correctly, which not only affects the environment negatively by causing the extinction of different species, polluting the water bodies, and contributing to climate change, but also exacerbates challenges related to low NUE. To get a better understanding of the problem and find out potential solutions, the authors have reviewed the factors influencing the adoption of sustainable nitrogen management technologies. The outcome indicated that the adoption of such technologies did not depend entirely on the technological advancements, but was rather a result of a complex interplay of various economic, social, behavioural, technical, institutional, and environmental factors. Thus, the main recommendation for reform is to abandon single-dimensionality in strategy and adopt integrated, participatory, and long-term approaches that empower farmers through supportive policies, innovative financing mechanisms, accessible and user-friendly technologies, and flexible advisory systems that tackle the main behavioural and economic barriers. This will enhance food security while preserving healthy and resilient ecosystems. The review has implications not only for agronomic practices and policy formulation, but also for information and knowledge management practitioners and researchers. The widespread use of digital nitrogen management tools, advisory services, and social learning networks highlights the need for efficient information systems and digital libraries capable of organizing, curating, and delivering credible, context-specific nitrogen management information to farmers and other stakeholders. The findings also provide scope for future innovations in information and knowledge management, including the development of farmer-centric platforms, the integration of scientific and indigenous knowledge systems, and the evaluation of different information delivery models in influencing technology adoption, nitrogen use efficiency, and environmental sustainability.

Acknowledgment

This research work was undertaken as part of the requirements for the award of a Ph.D. degree from KIIT School of Rural Management, KIIT Deemed to be University. I sincerely thank Prof. Damodar Jena (Ph.D. Guide), Prof. Priyanka Mishra, and the co-authors for their valuable guidance throughout the research journey.

References

[1] Adeleke, R. A., Raimi, A. R., Roopnarain, A., & Mokubedi, S. M. (2019). Status and prospects of bacterial inoculants for sustainable management of agroecosystems. In *Biofertilizers for sustainable agriculture and environment* (pp. 137-172). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-18933-4_7

[2] Ali, A., Jabeen, N., Farruhbek, R., Chachar, Z., Laghari, A. A., Chachar, S., ... & Yang, Z. (2025). Enhancing nitrogen use efficiency in agriculture by integrating agronomic practices and genetic advances. *Frontiers in Plant Science*, *16*, 1543714. https://doi.org/10.3389/fpls.2025.1543714

[3] Amadu, F. O., McNamara, P. E., & Davis, K. E. (2021). Soil health and grain yield impacts of climate resilient agriculture projects: Evidence from southern Malawi. *Agricultural systems*, *193*, 103230. https://doi.org/10.1016/j.agsy.2021.103230

[4] Anderson, W., Johansen, C., & Siddique, K. H. (2016). Addressing the yield gap in rainfed crops: a review. *Agronomy for sustainable development*, *36*(1), 18. https://doi.org/10.1007/s13593-015-0341-y

[5] Arizo-García, P., Castiñeira-Ibáñez, S., Tarrazó-Serrano, D., Franch, B., Rubio, C., & San Bautista, A. (2025). Use of Sentinel-2 Images to Elaborate a VRT Sensor-Based and Map-Based Nitrogen Fertilization in Wheat and Barley Crops. *Applied Sciences*, *15*(21), 11646.https://doi.org/10.3390/app152111646

[6] Aryal, J. P., Rahut, D. B., Sapkota, T. B., Khurana, R., & Khatri-Chhetri, A. (2020). Climate change mitigation options among farmers in South Asia: JP Aryal et al. *Environment, Development and Sustainability*, *22*(4), 3267-3289. https://doi.org/10.1007/s10668-019-00345-0

[7] Aryal, J. P., Sapkota, T. B., Krupnik, T. J., Rahut, D. B., Jat, M. L., & Stirling, C. M. (2021). Factors affecting farmers' use of organic and inorganic fertilizers in South Asia. *Environmental Science and Pollution Research*, *28*(37), 51480-51496. https://doi.org/10.1007/s11356-021-13975-7

[8] Azam, M. S., & Shaheen, M. (2019). Decisional factors driving farmers to adopt organic farming in India: a cross-sectional study. *International Journal of Social Economics*, *46*(4), 562-580. https://doi.org/10.1108/IJSE-05-2018-0282

[9] Becker, M., Ladha, J. K., & Ali, M. (1995). Green manure technology: Potential, usage, and limitations. A case study for lowland rice. *Plant and soil*, *174*(1), 181-194. https://doi.org/10.1007/BF00032246

[10] Begho, T., Glenk, K., Anik, A. R., & Eory, V. (2022). A systematic review of factors that influence farmers' adoption of sustainable crop farming practices: Lessons for sustainable nitrogen management in South Asia. *Journal of Sustainable Agriculture and Environment*, *1*(2), 149-160. https://doi.org/10.1002/sae2.12016

[11] Bhattacharyya, S., Rai, C. K., Patnaik, N. M., Verma, R. K., & Roy, P. (2023). Adoption of sustainable dryland technologies for improving livelihood of farmers in developing countries. In *Enhancing Resilience of Dryland Agriculture Under Changing Climate: Interdisciplinary and Convergence Approaches* (pp. 597-624). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9159-2_30

[12] Boyer, C. N., Wade Brorsen, B., Solie, J. B., & Raun, W. R. (2011). Profitability of variable rate nitrogen application in wheat production. *Precision Agriculture*, *12*(4), 473-487. https://doi.org/10.1007/s11119-010-9190-5

[13] Cantarella, H., Otto, R., Soares, J. R., & de Brito Silva, A. G. (2018). Agronomic efficiency of NBPT as a urease inhibitor: A review. *Journal of advanced research*, *13*, 19-27. https://doi.org/10.1016/j.jare.2018.05.008

[14] Castro-Rincon, E., Mojica-Rodríguez, J. E., Carulla-Fornaguera, J. E., & Lascano-Aguilar, C. E. (2018). Green legume fertilizers: integration in agricultural and livestock systems in the tropics. *Agronomia Mesoamericana*, *29*(3), 711-729. http://dx.doi.org/10.15517/ma.v29i3.31612

[15] Christianson, L., Knoot, T., Larsen, D., Tyndall, J., & Helmers, M. (2014). Adoption potential of nitrate mitigation practices: an ecosystem services approach. *International Journal of Agricultural Sustainability*, *12*(4), 407-424. https://doi.org/10.1080/14735903.2013.835604

[16] Coskun, D., Britto, D. T., Shi, W., & Kronzucker, H. J. (2017). Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. *Nature plants*, *3*(6), 17074. https://doi.org/10.1038/nplants.2017.74

[17] Craswell, E. T., Sajjapongse, A., Howlett, D. J. B., & Dowling, A. J. (1997). Agroforestry in the management of sloping lands in Asia and the Pacific. *Agroforestry systems*, *38*(1), 121-137. https://doi.org/10.1023/A:1005960612386

[18] Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N. J., Jacobsen, B. H., ... & Vejre, H. (2014). Policies for agricultural nitrogen management—trends, challenges and prospects for improved efficiency in Denmark. *Environmental Research Letters*, *9*(11), 115002. https://doi.org/10.1088/1748-9326/9/11/115002

[19] Das, K., Prasanna, R., & Saxena, A. K. (2017). Rhizobia: a potential biocontrol agent for soilborne fungal pathogens. *Folia microbiologica*, *62*(5), 425-435. https://doi.org/10.1007/s12223-017-0513-z

[20] Das, S., Jena, D., Mishra, P., Mishra, C., Rout, P., Subraya, G. H., ... & Singh, A. (2025). Home Gardens into Climate Resilience Strategies: Insights from Tribal Communities in Keonjhar, Odisha. *Journal of Environmental & Earth Sciences*, *7*(7). https://doi.org/10.30564/jees.v7i7.9923

[21] Dsouza, A., & Mishra, A. (2016). Adoption and abandonment of conservation Technologies in Developing Economies: the case of South Asia. https://doi.org/10.22004/AG.ECON.235243

[22] Fraters, B., Hooijboer, A. E. J., Vrijhoef, A., Claessens, J., Kotte, M. C., Rijs, G. B. J., ... & Bosma, J. N. (2016). Agricultural practice and waterquality in the Netherlands: status (2012-2014) and trend (1992-2014): Monitoring results for Nitrates Directive reporting. https://doi.org/10.13140/RG.2.2.10385.02403

[23] Gallardo, M., Elia, A., & Thompson, R. B. (2020). Decision support systems and models for aiding irrigation and nutrient management of vegetable crops. *Agricultural Water Management*, *240*, 106209. https://doi.org/10.1016/j.agwat.2020.106209

[24] Geussens, K., Van den Broeck, G., Vanderhaegen, K., Verbist, B., & Maertens, M. (2019). Farmers' perspectives on payments for ecosystem services in Uganda. *Land Use Policy*, *84*, 316-327. https://doi.org/10.1016/j.landusepol.2019.03.020

[25] Gnahoua, J. B. G., Ettien, D. J. B., N'zué, B., De Neve, S., & Boeckx, P. (2016). Assessment of low-input technologies to improve productivity of early harvested cassava in Côte d'Ivoire. *Agroecology and Sustainable Food Systems*, *40*(9), 941-964. https://doi.org/10.1080/21683565.2016.1209610

[26] Hamid, F., Yazdanpanah, M., Baradaran, M., Khalilimoghadam, B., & Azadi, H. (2021). Factors affecting farmers' behavior in using nitrogen fertilizers: society vs. farmers' valuation in southwest Iran. *Journal of Environmental Planning and Management*, *64*(10), 1886-1908. https://doi.org/10.1080/09640568.2020.1851175

[27] Huang, J., Huang, Z., Jia, X., Hu, R., & Xiang, C. (2015). Long-term reduction of nitrogen fertilizer use through knowledge training in rice production in China. *Agricultural Systems*, *135*, 105-111. https://doi.org/10.1016/j.agsy.2015.01.004

[28] Kheir, A. M., Alkharabsheh, H. M., Seleiman, M. F., Al-Saif, A. M., Ammar, K. A., Attia, A., ... & Schillaci, C. (2021). Calibration and validation of AQUACROP and APSIM models to optimize wheat yield and water saving in arid regions. *Land*, *10*(12), 1375. https://doi.org/10.3390/land10121375

[29] Krishnamoorthy, V., & Rajiv, S. (2017). *An eco-friendly top-down approach to nutrient incorporated electrospun seed coating for superior germination potential*. *Journal of Advanced Applied Science Research, 1*(7). https://doi.org/10.46947/joaasr17201754

[30] Liu, J., Cai, H., Chen, S., Pi, J., & Zhao, L. (2023). A review on soil nitrogen sensing technologies: challenges, progress and perspectives. *Agriculture*, *13*(4), 743. https://doi.org/10.3390/agriculture13040743

[31] Liu, Y., Mancuso, G., Petrotto, L., Lavrnić, S., Dong, Z., Tian, Y., ... & Toscano, A. (2025). AI-driven solutions in wastewater treatment and agricultural reuse systems: A comprehensive review. *Journal of Environmental Management*, *393*, 127008. https://doi.org/10.1016/j.jenvman.2025.127008

[32] Lundy, M. E., Pittelkow, C. M., Linquist, B. A., Liang, X., van Groenigen, K. J., Lee, J., ... & van Kessel, C. (2015). Nitrogen fertilization reduces yield declines following no-till adoption. *Field Crops Research*, *183*, 204-210. https://doi.org/10.1016/j.fcr.2015.07.023

[33] Macdonald, B. C., Latimer, J. O., Schwenke, G. D., Nachimuthu, G., & Baird, J. C. (2018). The current status of nitrogen fertiliser use efficiency and future research directions for the Australian cotton industry. *Journal of Cotton Research*, *1*(1), 15. https://doi.org/10.1186/s42397-018-0015-9

[34] Martínez-Dalmau, J., Berbel, J., & Ordóñez-Fernández, R. (2021). Nitrogen fertilization. A review of the risks associated with the

inefficiency of its use and policy responses. *Sustainability*, *13*(10), 5625. https://doi.org/10.3390/su13105625

[35] Mermut, A. R. (2012). Crop diversification practices in saskatchewan, Canada. In *Crop Production for Agricultural Improvement* (pp. 515-522). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-4116-4_20

[36] Mishra, C., Jena, D., Parida, N. R., Subudhi, R. N., Pani, S. K., Giri, V. V., & Daoun, A. (2024). Adoption of fertilizer technology for rice cultivation in Kalahandi District, Odisha. *Multidisciplinary Science Journal*, *6*(12), 1-9. https://doi.org/10.31893/multiscience.2024294

[37] Munz, J., & Schuele, H. (2022). Influencing the success of precision farming technology adoption—A model-based investigation of economic success factors in small-scale agriculture. *Agriculture*, *12*(11),1773. https://doi.org/10.3390/agriculture12111773

[38] Narwal, S. S. (2006). Allelopathy in ecological sustainable agriculture. In *Allelopathy: a physiological process with ecological implications* (pp. 537-564). Dordrecht: Springer Netherlands. https://doi.org/10.1007/1-4020-4280-9_24

[39] Negi, D., Verma, S., Singh, S., Daverey, A., & Lin, J. G. (2022). Nitrogen removal via anammox process in constructed wetland–a comprehensive review. *Chemical Engineering Journal*, *437*, 135434. https://doi.org/10.1016/j.cej.2022.135434

[40] Nie, L., Peng, S., Chen, M., Shah, F., Huang, J., Cui, K., & Xiang, J. (2012). Aerobic rice for water-saving agriculture. A review. *Agronomy for Sustainable Development*, *32*(2), 411-418. https://doi.org/10.1007/s13593-011-0055-8

[41] Olum, S., Gellynck, X., Juvinal, J., Ongeng, D., & De Steur, H. (2020). Farmers' adoption of agricultural innovations: A systematic review on willingness to pay studies. *Outlook on Agriculture*, *49*(3), 187-203. https://doi.org/10.1177/0030727019879453

[42] Pan, W. L., Schillinger, W. F., Young, F. L., Kirby, E. M., Yorgey, G. G., Borrelli, K. A., ... & Eigenbrode, S. D. (2017). Integrating historic agronomic and policy lessons with new technologies to drive farmer decisions for farm and climate: the case of inland Pacific Northwestern US. *Frontiers in Environmental Science*, *5*, 76. https://doi.org/10.3389/fenvs.2017.00076

[43] Pani, S. K., Jena, D., & Parida, N. R. (2020). Agricultural sustainability and sustainable agribusiness model: A review on economic and environmental perspective. *International Journal of Modern Agriculture*, *9*(4), 875-883.

[44] Pani, S. K., Jena, D., Subudhi, R., & Rath, J. P. (2021). Nitrogen fertilizer use in agriculture among marginal and small farmers in India: review of important drivers. *International Journal of Modern Agriculture*, (10).

[45] Papadopoulos, A., Kalivas, D., & Hatzichristos, T. (2011). Decision support system for nitrogen fertilization using fuzzy theory. *Computers and electronics in agriculture*, *78*(2), 130-139. https://doi.org/10.1016/j.compag.2011.06.007

[46] Peng, S., Buresh, R. J., Huang, J., Zhong, X., Zou, Y., Yang, J., ... & Dobermann, A. (2010). Improving nitrogen fertilization in rice by sitespecific N management. A review. *Agronomy for sustainable development*, *30*(3), 649-656. https://doi.org/10.1051/agro/2010002

[47] Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., ... & Torero, M. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nature Sustainability*, *3*(10), 809-820. https://doi.org/10.1038/s41893-020-00617-y

[48] Prakash, R. J., Narayan, S. R., Damodar, J., & Kumar, P. S. (2021). Nitrogen fertilizer use in Indian agriculture: A policy analysis. *Advances in Management, 14*(1), 40-47.

[49] Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1491), 447-465. https://doi.org/10.1098/rstb.2007.2163

[50] Ren, C., Zhang, X., Reis, S., & Gu, B. (2022). Socioeconomic barriers of nitrogen management for agricultural and environmental sustainability. *Agriculture, Ecosystems & Environment*, *333*, 107950. https://doi.org/10.1016/j.agee.2022.107950

[51] Rossel, R. A. V., & Bouma, J. (2016). Soil sensing: A new paradigm for agriculture. *Agricultural systems*, *148*, 71-74. https://doi.org/10.1016/j.agsy.2016.07.001

[52] Sharma, N., Kochar, M., Allardyce, B. J., Rajkhowa, R., & Agrawal, R. (2024). Unveiling the potential of cellulose nanofibre based nitrogen fertilizer and its transformative effect on Vigna radiata (Mung Bean): nanofibre for sustainable agriculture. *Frontiers in Plant Science*, *15*, 1336884. https://doi.org/10.3389/fpls.2024.1336884

[53] Sheng, J., Khan, A. A., Zheng, S., & Lu, Q. (2021). Evaluating adoption of information communication technology in agricultural green production to increase net returns. *Polish Journal of Environmental Studies*, *30*(6), 5723-5738. https://doi.org/10.15244/pjoes/134543

[54] Shortle, J. S., Mihelcic, J. R., Zhang, Q., & Arabi, M. (2020). Nutrient control in water bodies: A systems approach. *Journal of Environmental Quality*, *49*(3), 517-533. https://doi.org/10.1002/jeq2.20022

[55] Shu, R., Guan, Y., & Liu, B. (2025). Preparation of nitrogen-doped reduced graphene oxide/zinc ferrite@ nitrogen-doped carbon composite for broadband and highly efficient electromagnetic wave absorption. *Journal of Materials Science & Technology*, *214*, 16-26. https://doi.org/10.1016/j.jmst.2024.07.006

[56] Sibanda, M., Mutanga, O., & Rouget, M. (2017). Testing the capabilities of the new WorldView-3 space-borne sensor's red-edge spectral band in discriminating and mapping complex grassland management treatments. *International Journal of Remote Sensing*, *38*(1), 1-22. https://doi.org/10.1080/01431161.2016.1259678

[57] Singh, B. (2022). Nitrogen use efficiency in crop production in India: Trends, issues, and challenges. *Agric. Res*, *12*, 32-44. https://doi.org/10.1007/s40003-022-00626-7

[58] Skaalsveen, K., Ingram, J., & Urquhart, J. (2020). The role of farmers' social networks in the implementation of no-till farming practices. *Agricultural Systems*, *181*, 102824. https://doi.org/10.1016/j.agsy.2020.102824

[59] So, H. B., Kirchhof, G., Bakker, R., & Smith, G. D. (2001). Low input tillage/cropping systems for limited resource areas. *Soil and Tillage Research*, *61*(1-2), 109-123. https://doi.org/10.1016/S0167-1987(01)00182-9

[60] Solomon, B. D. (2010). Biofuels and sustainability. *Annals of the New York Academy of Sciences*, *1185*(1), 119-134. https://doi.org/10.1111/j.1749-6632.2009.05279.x

[61] Timlin, D., Paff, K., & Han, E. (2024). The role of crop simulation modeling in assessing potential climate change impacts. *Agrosystems, Geosciences & Environment*, *7*(1), e20453. https://doi.org/10.1002/agg2.20453

[62] Usman, M., Sanaullah, M., Ullah, A., Li, S., & Farooq, M. (2022). Nitrogen pollution originating from wastewater and agriculture: advances in treatment and management. *Reviews of Environmental Contamination and Toxicology*, *260*(1), 9. https://doi.org/10.1007/s44169-022-00010-0

[63] Van Grinsven, H. J., Tiktak, A., & Rougoor, C. W. (2016). Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. *NJAS-Wageningen Journal of Life Sciences*, *78*, 69-84. https://doi.org/10.1016/j.njas.2016.03.010

[64] Velten, S., Leventon, J., Jager, N., & Newig, J. (2015). What is sustainable agriculture? A systematic review. *Sustainability*, *7*(6), 7833-7865. https://doi.org/10.3390/su7067833

[65] Verhulst, N., Kienle, F., Sayre, K. D., Deckers, J., Raes, D., Limon-Ortega, A., ... & Govaerts, B. (2011). Soil quality as affected by tillage-residue management in a wheat-maize irrigated bed planting system. *Plant and soil*, *340*(1), 453-466. https://doi.org/10.1007/s11104-010-0618-5

[66] Wang, H., Ren, H., Zhang, L., Zhao, Y., Liu, Y., He, Q., ... & Liu, P. (2023). A sustainable approach to narrowing the summer maize yield gap experienced by smallholders in the North China Plain. *Agricultural Systems*, *204*, 103541. https://doi.org/10.1016/j.agsy.2022.103541

[67] Wang, J., Lali, M. N., Dong, Z., Xiong, H., Wang, Y., Zhao, L., ... & Zhang, Y. (2024). Organic waste recycling for green and sustainable nitrogen management of fruit production systems in China. *Agricultural Systems*, *218*, 103959. https://doi.org/10.1016/j.agsy.2024.103959

[68] Wei, G., Kong, X., & Wang, Y. (2022). Will joining cooperative promote farmers to replace chemical fertilizers with organic fertilizers?. *International Journal of Environmental Research and Public Health*, *19*(24), 16647. https://doi.org/10.3390/ijerph192416647

[69] Wei, S., Ledgard, S., Fan, J., Tian, Y., & Dong, H. (2024). Carbon footprints, mitigation effects and economic performance of dairy farm systems in Inner Mongolia. *Agricultural Systems*, *214*, 103835. https://doi.org/10.1016/j.agsy.2023.103835

[70] Wittmann, F., Eder, M., Schreck, K., & Grassauer, F. (2024). Modelled impacts of farm-level adaptations in response to changed dietary patterns. *Applied Economics*, *56*(26), 3166-3180. https://doi.org/10.1080/00036846.2023.2205099

[71] Wood, L., Lubell, M., Rudnick, J., Khalsa, S. D. S., Sears, M., & Brown, P. H. (2022). Mandatory information-based policy tools facilitate California farmers' learning about nitrogen management. *Land use policy*, *114*, 105923. https://doi.org/10.1016/j.landusepol.2021.105923

[72] Wu, P., Zhao, G., Liu, F., Ahmad, S., Fan, T., Li, S., ... & Cai, T. (2021). Agronomic system for stabilizing wheat yields and enhancing the sustainable utilization of soil: A 12-year in-situ rotation study in a semi-arid agro-ecosystem. *Journal of Cleaner Production*, *329*, 129768. https://doi.org/10.1016/j.jclepro.2021.129768

[73] Xia, L., Lam, S. K., Chen, D., Wang, J., Tang, Q., & Yan, X. (2017). Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis. *Global change biology*, *23*(5), 1917-1925. https://doi.org/10.1111/gcb.13455

[74] Xiong, W., van der Velde, M., Holman, I. P., Balkovic, J., Lin, E., Skalský, R., ... & Obersteiner, M. (2014). Can climate-smart agriculture reverse the recent slowing of rice yield growth in China?. *Agriculture, ecosystems & environment*, *196*, 125-136. https://doi.org/10.1016/j.agee.2014.06.01