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REVIEW ARTICLE

Traditional knowledge in soil management and water conservation: Perspectives from the agrodiverse state of Uttar Pradesh, India

Himanshu Sahu[1,2,3], Pooja Purohit[1,2], Arun Pratap Mishra[4]*, Amit Kumar[5], Purnendu Sardar[6], Bojan Đurin[7], and Upaka Rathnayake[8]*

[1]Department of Animal Ecology and Conservation Biology, Wildlife Institute of India, Dehradun, Uttarakhand, India
[2]Research and Development, Bhomya Foundation, Dehradun, Uttarakhand, India
[3]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, Uttar Pradesh, India
[4]Department of Forestry and Remote Sensing, Earthtree Enviro Private Limited, Shillong, Meghalaya, India
[5]Department of Habitat Ecology, Wildlife Institute of India, Dehradun, Uttarakhand, India
[6]Department of Physical Geography and Ecosystem Science (INES), Centre for Advanced Middle Eastern Studies, Lund University, Lund, Sweden
[7]Department of Civil Engineering, University North, Varazdin, Croatia
[8]Department of Civil Engineering and Construction, Faculty of Engineering and Design, Atlantic Technological University Sligo, Sligo, Ireland

***Corresponding authors:** Arun Pratap Mishra (arunpratap7371@gmail.com);
Upaka Rathnayake (upaka.rathnayake@atu.ie)

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Abstract: Soil management is a crucial aspect of sustainable agriculture, and traditional knowledge has played a pivotal role in shaping practices that maintain soil health over time. This study examines the significance of traditional soil management techniques used in Uttar Pradesh, India, and assesses their effectiveness in addressing modern agricultural challenges. The primary objective of this analysis is to investigate how indigenous practices, such as crop rotation, intercropping, organic manure application, and traditional water conservation techniques, contribute to soil fertility and sustainability. By examining these traditional methods, the study aims to assess their potential for integration with contemporary agricultural practices to enhance overall soil health and agricultural productivity. A comprehensive analysis of existing literature was conducted to synthesize findings from various studies on traditional soil management practices in Uttar Pradesh. The analysis highlights the mechanisms by which these practices affect soil properties and fertility and identifies the strengths and limitations associated with their use. The findings reveal that traditional methods offer significant benefits, including enhanced soil structure, improved nutrient availability, and increased moisture retention. However, challenges such as limited adoption of modern technologies and varying regional practices are also noted. The integration of traditional knowledge with modern techniques is evaluated as a means to address these challenges and optimize soil management strategies. This analysis bridges the gap between traditional knowledge and contemporary agricultural practices, providing valuable insights for policymakers, researchers, and practitioners. The study underscores the importance of integrating traditional soil management practices with modern approaches to foster sustainable agriculture in Uttar Pradesh and similar regions.

Keywords: Crop rotation; Indigenous practices; Organic manuring; Soil fertility; Soil management; Sustainable agriculture; Traditional knowledge

1. Introduction

Soil management is a keystone of sustainable agriculture, influencing not only crop productivity but also broader ecosystem functions and resilience.[1,2] Effective soil management practices are crucial for maintaining soil fertility, preventing soil degradation, and ensuring food security, particularly in regions that rely heavily on agriculture for their livelihoods.[3,4] In the contemporary discourse on sustainable agriculture, traditional knowledge has emerged as a crucial component of soil management strategies, particularly in developing countries where access to modern agricultural technologies may be limited or economically unfeasible.[5,6]

Traditional knowledge refers to the cumulative form of knowledge, practices, and beliefs developed by indigenous and local communities over centuries, often transmitted verbally across generations.[7,8] This knowledge is deeply rooted in the cultural and ecological contexts of these communities, offering time-tested solutions for soil management that are adapted to specific local conditions.[9,10] In India, a country with a rich agricultural heritage, traditional soil management practices have been integral to sustaining agricultural productivity and ensuring environmental sustainability.[11,12] These practices encompass a range of techniques, including crop rotation, intercropping, organic manure application, water conservation, and agroforestry, all of which contribute to the long-term health of soils.[13]

Uttar Pradesh, one of India's most agriculturally significant states, presents a diverse agroecological landscape that includes the fertile Gangetic plains, the arid Bundelkhand region, and the humid Terai region. Each region has developed unique traditional soil management practices that are finely tuned to local environmental conditions and agricultural needs.[14-17] For instance, in the Gangetic plains, traditional crop rotation systems involving cereals and legumes have been demonstrated to maintain soil fertility and reduce the need for synthetic fertilizers.[18,19] In Bundelkhand, a region prone to drought, traditional water harvesting techniques, such as the construction of check dams and contour bunding, have played a crucial role in preventing soil erosion and sustaining agriculture under challenging climatic conditions.[20-22]

Despite the proven benefits of these traditional practices, the Green Revolution of the 1960s and 1970s marked a significant shift in agricultural practices across India, including Uttar Pradesh. The widespread adoption of high-yielding varieties (HYVs), chemical fertilizers, and pesticides has led to substantial increases in crop productivity but also introduced new challenges, such as soil degradation, loss of biodiversity, and increased environmental pollution.[23,24] These changes have raised concerns about the sustainability of modern agricultural practices and have prompted a renewed interest in integrating traditional knowledge with contemporary soil management strategies.[25,26]

Recent studies have highlighted the importance of traditional knowledge in promoting sustainable soil management and enhancing the resilience of agricultural systems in the face of climate change.[27,28] Traditional practices, such as the use of organic manure and crop residues, have been found to improve soil structure, increase organic matter content, and enhance microbial activity, all of which are crucial for maintaining soil health.[1,29-31] Moreover, these practices often employ low-input methods that reduce dependence on external inputs, making them particularly relevant for resource-poor farmers in regions such as Uttar Pradesh.[32-34]

The integration of traditional knowledge with modern soil management techniques offers a promising pathway for achieving sustainable agriculture in Uttar Pradesh. Such integration can enhance the effectiveness of soil conservation efforts, reduce the environmental impact of farming, and improve the livelihoods of smallholder farmers.[35,36] However, this approach also presents challenges, including the need to document and validate traditional practices, overcome institutional barriers, and address the erosion of traditional knowledge in the face of rapid socioeconomic changes.[8,37]

Considering the aforementioned aspects in view, the current communication aims to provide a comprehensive analysis of the role of traditional knowledge in soil management in Uttar Pradesh, with a focus on its relevance, challenges, and potential for integration with modern agricultural practices. By synthesizing existing literature and examining case studies from various regions of Uttar Pradesh, this article aims to contribute to the ongoing discourse on sustainable agriculture and the preservation of traditional knowledge in the context of contemporary challenges.[13,38,39] The findings of this analysis are expected to inform policy recommendations and guide future research efforts aimed at enhancing the sustainability of soil management practices in India and beyond.

2. Methods

2.1. Study area

This study focuses on Uttar Pradesh, India, a state known for its agricultural diversity and rich traditional knowledge in soil and water conservation. Uttar Pradesh is located in northern India, covering an area of 243,286 km^2, making it the fourth-largest state in the country. The state lies between 23°52'N and 31°28'N latitude and 77°3'E and 84°39'E longitude, bordered by Uttarakhand and Nepal to the north, Bihar to the east, Madhya Pradesh to the south, and Rajasthan, Haryana, and Delhi to the west. The sub-tropical climate in Uttar Pradesh features summer heat, monsoon precipitation, and a mild winter season, while annual rainfalls reach 990 mm but vary between different areas. The four primary waterways of Uttar Pradesh consist of the Ganga, Yamuna, Gomti, and Ghagra, which serve essential functions for irrigation and water management. The state spans nine agroclimatic zones, which extend from Terai in the northern end to Bundelkhand in the southern portion and exhibit different soil characteristics, together with unique cultivation practices and water preservation priorities.[176]

2.2. Systematic review

For this review, we performed a systematic literature search from various database sources, including Web of Science, Scopus, and Google Scholar, using keywords or combinations of words, such as "traditional knowledge," "indigenous knowledge," "soil management," "water conservation," "agriculture in Uttar Pradesh," and "agricultural practices in north India." Our original search revealed over 200 articles, which were screened by title and abstract to determine eligibility. We applied inclusion criteria based on studies on traditional soil and water conservation practices for Uttar Pradesh published in peer-reviewed journals or credible sources. Studies that were not empirical, not regional, or did not analyze traditional practices were excluded. Based on the above criteria, we included a total of 50 published articles for detailed analysis. The data extraction aimed to identify relevant traditional practices, efficacy, cultural importance, and the applicability of conventional practices to modern conservation strategies. The findings were synthesized to highlight the most prevalent soil and water conservation methods used in Uttar Pradesh and their potential integration with contemporary approaches. This methodology ensures a comprehensive understanding of traditional knowledge in soil and water conservation, contributing valuable insights for sustainable agricultural practices in the state.

3. Traditional soil management practices

3.1. Traditional knowledge and soil management

Traditional knowledge in soil management encompasses a diverse array of practices deeply intertwined with the cultural and ecological contexts of specific regions.[40,41] These practices, which have been developed and refined over centuries, include crop rotation, intercropping, organic manuring, and water conservation techniques.[42] They are tailored to local environmental conditions and contribute significantly to soil health and sustainability. This section provides an in-depth analysis of these traditional practices, emphasizing their scientific foundations and relevance to contemporary soil management challenges. A comprehensive flowchart of the soil management process is presented in Figure 1 and Table 1.

3.2. Crop rotation and intercropping

A traditional agricultural method is crop rotation, which entails planting several crops in succession in the same field throughout different growing seasons.[43,44] This practice enhances soil fertility and structure by alternating crops with varying nutrient requirements and root structures.[45-47] Traditional crop rotation systems often include a combination of cereals, legumes, and root crops. For instance, in Uttar Pradesh, rotations involving wheat, rice, and pulses are typical.[48]

Crop rotation offers numerous well-documented benefits, including healthier soils, improved crop yields, and better pest and disease management. Leguminous crops, such as pulses, fix atmospheric nitrogen in the soil, reducing the need for synthetic fertilizers and improving soil nitrogen levels.[49-51] In addition, rotation helps in disrupting pest and disease cycles, thereby reducing the need for chemical pest control.[24] Scientific studies have demonstrated that crop rotation can enhance soil organic matter content and improve soil structure, thereby contributing to overall soil health (Figure 2).[52-54]

Intercropping, the practice of growing two or more crops simultaneously in the same field, complements crop rotation by enhancing biodiversity and reducing the risk of soil depletion.[36] This practice can optimize resource use, as different crops may utilize soil nutrients, water, and light in complementary ways.[55,56] In Uttar Pradesh, intercropping systems often involve combinations, such as maize and legumes, which can improve soil nitrogen content and reduce pest populations.[57-60] Intercropping has been demonstrated to enhance soil fertility and productivity by increasing soil microbial diversity and activity.[61,62] Furthermore, this practice can help mitigate soil erosion by providing ground cover and reducing runoff.[56]

3.3. Organic manuring

Organic manuring involves the application of organic materials, such as compost, animal dung, and green

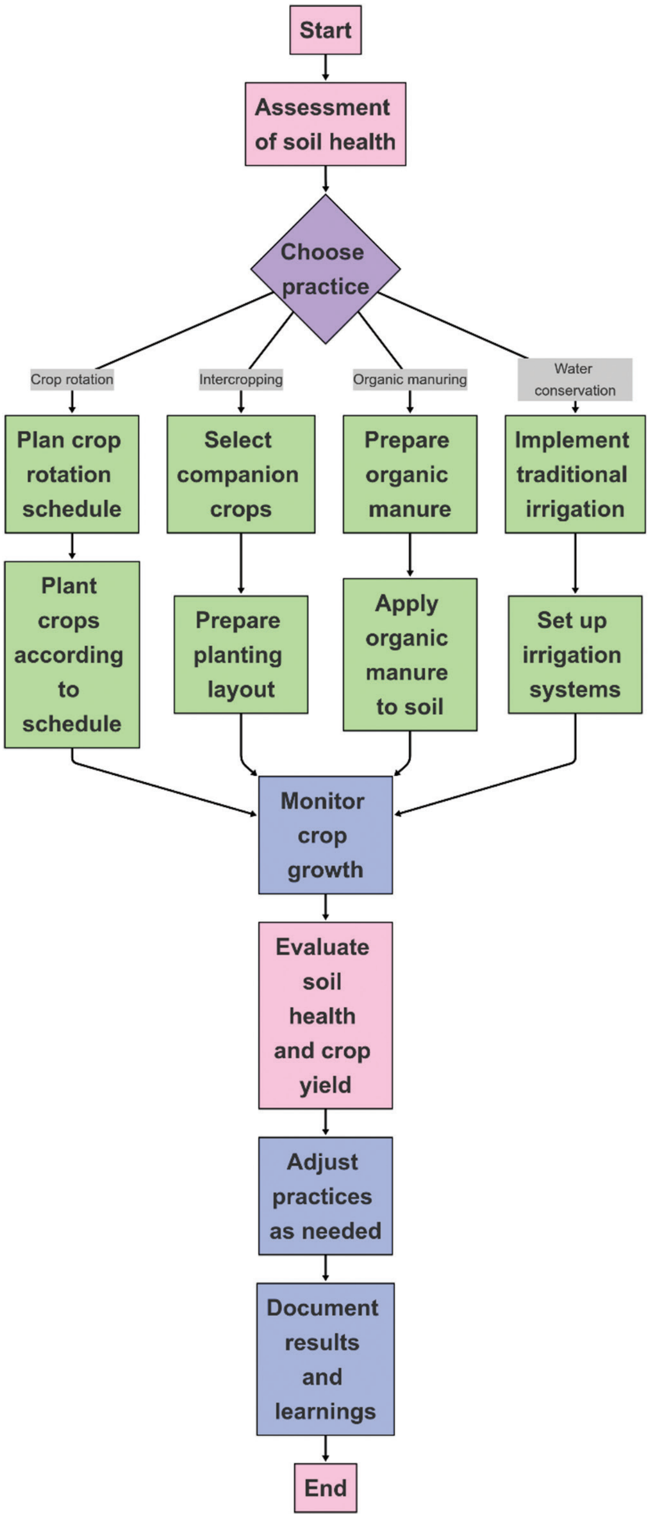

Figure 1. Decision-making process for implementing traditional soil management practices

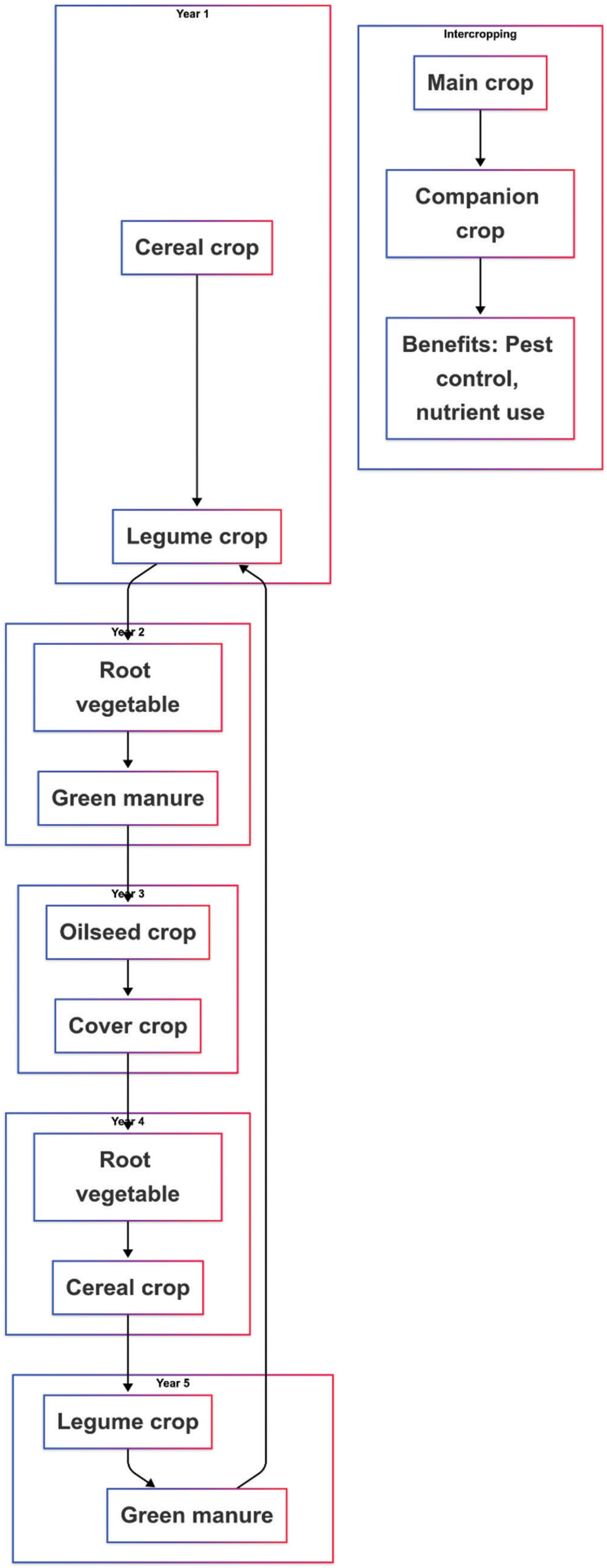

Figure 2. Crop rotation and intercropping pattern in India

manure, to improve soil fertility and structure.[63] This practice has been a mainstay of conventional soil management in Uttar Pradesh and many other regions.[64,65] A process flowchart of organic manuring is presented in Figure 3.

Compost and animal dung are rich in essential nutrients and organic matter, which enhance soil fertility

Table 1. Aspects of traditional soil management practices and modern techniques

Aspect	Traditional soil management practices	Modern techniques	References
Nutrient levels	Crop rotation: Enhances soil nutrient balance; reduces soil depletion	Chemical fertilizers: Quick nutrient supply but can lead to soil degradation	118,148
	Organic manuring: Increases organic matter and soil fertility	Precision agriculture: Optimizes nutrient application based on soil and crop needs, reducing excess use	149,150
	Intercropping: Enhances nutrient availability through complementary plant interactions	N/A	150,151
Soil erosion rates	Crop rotation: Helps reduce erosion by maintaining ground cover	Conventional tillage: Can increase erosion risk due to soil disturbance	32
	Organic manuring: Improves soil structure, reducing erosion	No-till farming: Reduces erosion by maintaining soil cover and structure	152
	Water conservation techniques: Methods like bunding reduce runoff and erosion	Contour plowing: Helps in reducing soil erosion by aligning plowing with the land's contour	153,154
Soil structure	Organic manuring: Improves soil texture and structure; increases moisture retention	Chemical amendments: Can improve soil texture but may degrade over time	155,156
	Crop rotation: Enhances soil structure by varying root types and depths	Soil health management: Incorporates practices to maintain and improve soil structure through minimal disturbance and organic inputs	157
	Intercropping: Diverse root systems improve soil structure	N/A	158
Yield outcomes	Crop rotation: Can increase yields over time by maintaining soil health	High-yield varieties: Generally lead to higher yields but may require more inputs	159,160
	Organic manuring: Often results in improved long-term yields due to enhanced soil fertility	Precision agriculture: Enhances yield by optimizing inputs and practices tailored to specific needs	161
	Intercropping: Increases overall yield by optimizing resource use	Green revolution technologies: Increased yields through improved varieties and chemical inputs	162
Sustainability	Crop rotation: Reduces dependency on chemical inputs and maintains soil health	Integrated pest management: Reduces reliance on chemical pesticides and promotes ecological balance	25,142,163
	Organic manuring: Promotes long-term soil health and reduces environmental impact	Sustainable intensification: Aims to increase productivity while minimizing environmental impacts	164
	Water conservation: Sustainable use of water resources	Technological innovations: Enhance sustainability through precise management and reduced resource use	165,166

Abbreviation: N/A: Not available.

by increasing the soil's nutrient-holding capacity and promoting microbial activity.[66,67] The use of compost improves soil structure, water-holding capacity, and nutrient availability, thereby supporting plant growth and reducing the need for synthetic fertilizers.[68-70] Similarly, animal dung serves as a valuable source of nitrogen, phosphorus, and potassium, which are essential for plant growth and development.[71,72]

Green manure, which involves incorporating cover crops such as legumes into the soil, enhances soil fertility and structure.[49,73,74] Green manure crops can fix atmospheric nitrogen, improve soil organic matter,

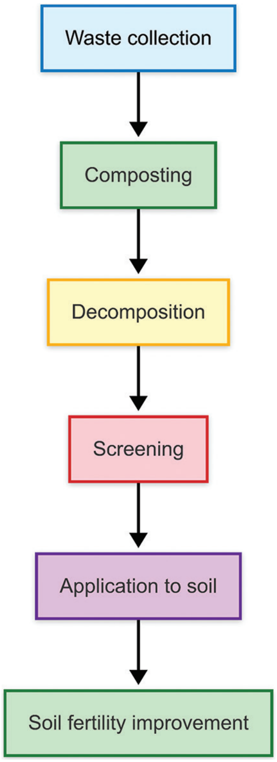

Figure 3. Process flowchart of organic manuring

and increase microbial biomass.[74] The incorporation of green manure into the soil also helps reduce soil erosion and promote nutrient cycling.[50,65]

3.4. Water conservation techniques

Traditional water conservation techniques have been employed in various regions to manage water resources effectively and prevent soil erosion.[75] These techniques are fundamental in water-scarce areas and regions prone to soil erosion, such as Bundelkhand in Uttar Pradesh.[20,76] Rainwater harvesting, contour bunding, check dams, percolation tanks, and step wells are standard methods that help with water storage, groundwater replenishment, and runoff reduction.[77] In addition to improving the amount of water available for everyday consumption and agriculture, these techniques are vital for maintaining livelihoods in regions vulnerable to drought.[78,79] To further enhance water conservation and climate change resilience, contemporary adaptations of these age-old practices are being combined with cutting-edge irrigation techniques and research methodologies.

Bunds, embankments, and check dams are traditional water conservation structures designed to capture and store runoff water, reducing soil erosion and promoting soil moisture retention.[80-83] These structures help control water flow, prevent the loss of valuable topsoil, and maintain soil fertility.[83] These structures play a crucial role in regulating water flow, preventing flash floods, and enhancing groundwater recharge.[84] Bunds, widely spread in agrarian landscapes, retain water flow and facilitate longer infiltration times while reducing crop loss from rapid runoff.[85] Check dams, the step-like barriers built across the streams and small rivers in arid regions, effectively trap sediments and regulate the velocity of the streams and also meet irrigation needs during the dry periods.[86]

In areas such as Bundelkhand and Rajasthan, these traditional practices play a crucial role in mitigating the effects of drought, enhancing soil fertility, and supporting rural livelihoods.[73] Bunds and check dams can play a crucial role in achieving long-term water security and sustainable agriculture when utilized in conjunction with contemporary principles of water management.

Terracing is another traditional technique used to manage water flow and reduce soil erosion on sloped land.[7,87] By creating level areas on sloped fields, terracing reduces runoff and encourages water infiltration, which helps maintain soil moisture and fertility.[88,89] This practice is particularly beneficial in areas with high rainfall and steep slopes, where soil erosion is a major concern.[90,91] By stabilizing slopes, terracing also improves soil fertility, enhances crop yields, and supports sustainable farming practices in challenging terrains.[92]

In contemporary applications, terracing can be utilized in conjunction with modern solutions, including stone bunds, vegetative buffer strips, and contour plowing, to enhance overall water retention and soil conservation.[93] It remains a key adaptation strategy in regions vulnerable to climate change, which is fundamental for sustaining agriculture and ensuring food security in the long term.[94]

3.5. Distribution of traditional soil management practices

Traditional soil management practices in India, including organic manure application, crop rotation, and intercropping, are crucial for promoting sustainable agriculture and maintaining soil health.[95] Organic manuring utilizes natural materials, such as compost and animal manure, to enhance soil fertility, while crop rotation replenishes nutrients and controls pests by alternating crops, often incorporating nitrogen-fixing legumes.[96] Intercropping, the practice of growing multiple crops together, enhances biodiversity and resource use.[97] Organic manuring is the most widely used method, followed by crop rotation, covering approximately 30 million hectares and contributing nearly 55% to the effectiveness of soil management.[98] Water conservation techniques, though harder to quantify in coverage, contribute 25% due to their importance in improving soil health.[99] Intercropping, practiced on roughly one million hectares, accounts for 20% of the overall impact.[100] Together, these methods reflect farmers' ecological knowledge, playing a significant role in sustainable agricultural systems and environmental conservation across India.[19] A distribution chart of various traditional soil management practices is presented in Figure 4.

3.6. Evolution of soil management practices

The evolution of soil management practices reflects a progression from early traditional methods to contemporary techniques aimed at enhancing soil fertility and sustainability.[101] Early traditional practices, dating back to the early 1900s, primarily involved basic crop rotation and organic manuring, which were essential for maintaining soil health in agrarian societies.[102,103] The introduction of essential organic fertilizers around 1920 marked the beginning of systematic efforts to improve soil fertility through the use of compost and green manure.[104] The mid-20th century witnessed the adoption of early modern agricultural practices, including the use of synthetic fertilizers and basic irrigation systems, which significantly transformed soil management.[105] By the 1970s, advanced traditional methods began to emerge, refining crop rotation and organic manuring techniques to enhance their effectiveness.[106] The 1980s introduced more sophisticated crop rotation techniques and the integration of pest management strategies, which further improved soil health.[107] The 1990s saw the adoption of integrated pest management, which aimed to balance pest control with minimal chemical use.[108] The turn of the millennium brought advancements in

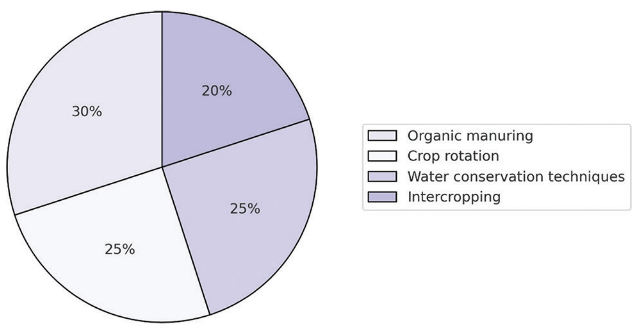

Figure 4. Distribution of traditional soil management practices

traditional methods, emphasizing sustainability and efficiency.[109] The 2010s marked the rise of precision agriculture, leveraging technology to optimize soil management practices.[110] Recent developments include advanced soil testing and monitoring technologies, which provide detailed insights into soil conditions and support more informed management decisions.[111] As of 2024, modern techniques continue to evolve, integrating cutting-edge technologies with traditional practices to foster more sustainable and productive soil management strategies.[112] A timeline of the evolution of soil management practices is presented in Figure 5.

4. Case studies from Uttar Pradesh

Uttar Pradesh, with its diverse agroclimatic zones, showcases a variety of traditional soil management practices that reflect the region's rich agricultural heritage.[113] This section presents detailed case studies from three distinct areas within Uttar Pradesh, each highlighting the effectiveness of traditional practices tailored to local environmental conditions. A tabular representation of the current state of scholarly work is presented in Table 2.

4.1. The Bundelkhand region

The Bundelkhand region, characterized by its semi-arid climate and frequent droughts, has a long history of employing traditional water conservation techniques to combat soil erosion and sustain agriculture. Contour bunding is one such practice where embankments are constructed along the contour lines of slopes to capture and slow down runoff water. This method reduces soil erosion, enhances water infiltration, and contributes to improved soil moisture retention. Research indicates that contour bunding can significantly mitigate soil loss and improve crop yields in Bundelkhand.[21,28] In addition, the construction of small check dams, or *Nadi* dams, has proven effective in capturing runoff water and recharging groundwater levels. These check dams help stabilize water availability for irrigation, thereby increasing agricultural productivity.[114,115] Studies have demonstrated that these traditional water conservation practices in Bundelkhand have led to significant improvements in water availability and soil health.[20,21,116]

4.2. The Gangetic plains

In the Gangetic plains, known for their fertile alluvial soils, traditional practices, such as crop rotation and organic manuring, play a crucial role in maintaining soil fertility and productivity. Crop rotation, specifically the

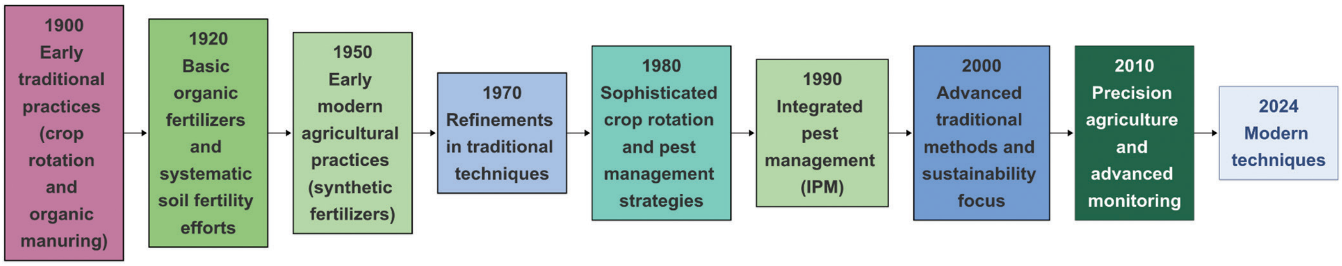

Figure 5. Timeline of the evolution of soil management practices

Table 2. Case studies on soil traditional management practices conducted in Uttar Pradesh

Case study	Location	Practice used	Results achieved	Observations	References
1	Village Nagla, Aligarh	Crop rotation	Increased soil fertility by 25%; reduced pest incidence by 30%	Effective in enhancing soil nutrient balance and pest control	167
2	Village Daryapur, Agra	Intercropping	Boosted crop yields by 20%; improved soil nutrient levels by 15%	Combined cultivation of legumes and cereals optimized soil fertility	168,169
3	Village Sadabad, Hathras	Organic manuring	Enhanced soil structure; increased crop productivity by 35%	Compost and green manure improved moisture retention and soil health	170
4	Village Kheri, Bulandshahr	Crop rotation + organic manuring	Reduced soil erosion by 40%; improved nutrient cycling by 30%	Integration of practices led to significant soil conservation and fertility	117,171
5	Village Rasoolpur, Etah	Traditional water conservation	Increased water retention by 25%; improved crop growth by 20%	Techniques, like bunding and check dams, were effective in semi-arid conditions	172
6	Village Raebareli, Raebareli	Crop rotation	Improved soil organic matter by 30%; decreased soil salinity	Rotation between legumes and cereals enhanced soil fertility	11
7	Village Mirzapur, Mirzapur	Organic manuring	Increased soil moisture by 20%; enhanced crop resilience	Organic manure application improved soil texture and moisture retention	173
8	Village Jalaun, Jalaun	Traditional water conservation	Reduced runoff by 30%; improved soil fertility	Traditional water management practices were effective in conserving water	174

rotation of rice with pulses, helps replenish soil nutrients and improve soil structure by breaking pest and disease cycles. This practice has been demonstrated to increase soil organic matter and nutrient availability, resulting in improved crop yields.[48,117] Organic manuring, involving the use of cow dung, compost, and other organic materials, is integral to soil management in this region. Organic manures enhance soil fertility by providing essential nutrients and stimulating microbial activity, which in turn supports sustainable agriculture.[118] Studies have demonstrated that organic manure results in better soil health and higher crop yields compared to chemical fertilizers.[119,120]

4.3. The Terai region

The Terai region, characterized by its heavy, clayey soils and high water table, employs unique traditional practices, such as raised beds and organic mulching, to manage soil moisture and prevent waterlogging. Raised bed farming involves creating elevated planting beds to improve soil drainage and aeration, crucial for managing excessive moisture in clayey soils. This technique has been demonstrated to improve crop yields and soil health by preventing waterlogging and promoting root growth.[121,122] Organic mulching, the application of organic materials, such as straw or leaf litter, helps conserve soil moisture, prevent erosion, and add organic matter to the soil. Mulching has been effective in maintaining soil structure and increasing water-holding capacity, thus supporting sustainable agricultural practices in the Terai region.[123,124] Studies have highlighted that organic mulching improves soil fertility and promotes beneficial microbial activity, resulting in improved crop performance.[6,125]

5. Relevance of traditional knowledge in modern agriculture

Traditional knowledge, with its deep roots in cultural and ecological contexts, remains highly relevant in modern agriculture, particularly in the realm of soil management. Despite the rapid advancements in agricultural technology and scientific research, many traditional practices offer compelling advantages that align with contemporary needs for sustainability and environmental stewardship.

5.1. Environmental sustainability and resilience

Traditional soil management practices often emphasize environmental sustainability, a concept that is increasingly crucial in the face of climate change. Techniques, such as crop rotation, organic manuring, and water conservation, deeply embedded in traditional knowledge contribute to soil health and resilience. For instance, crop rotation, a common practice in traditional agriculture, helps maintain soil fertility by preventing nutrient depletion and disrupting pest and disease cycles.[126,127] This practice aligns well with modern concepts of sustainable agriculture, which advocate for reducing reliance on chemical inputs and enhancing soil biodiversity.[128]

5.2. Low-cost and resource-efficient practices

Many traditional soil management practices are notably low-cost and resource-efficient. Organic manuring, utilizing locally available materials such as compost and animal dung, reduces the dependency on synthetic fertilizers, which can be expensive and environmentally harmful.[1,129] These practices are not only cost-effective but also enhance soil health by improving its organic matter content and microbial activity.[6,37] This is particularly relevant for smallholder farmers in developing regions who may have limited access to modern agricultural inputs.

5.3. Cultural and local adaptation

Traditional knowledge is inherently adapted to local environmental conditions and cultural practices. For example, water conservation techniques, such as bunding and check dams, which have been used for centuries in regions like Bundelkhand, are tailored to the specific hydrological and soil conditions of the area.[130,131] These practices often integrate indigenous knowledge of local weather patterns, soil types, and water resources, making them highly relevant and effective for local contexts.[132]

5.4. Integration with modern technologies

Integrating traditional knowledge with modern agricultural technologies can offer synergistic benefits. For instance, the use of raised beds in the Terai region, a traditional practice for managing clayey soils, can be complemented with modern irrigation systems to optimize water use and crop productivity.[133] Similarly, combining traditional organic manuring practices with precision agriculture techniques can enhance soil fertility while minimizing environmental impacts.[134] This integration can lead to more sustainable and resilient agricultural systems.

5.5. Addressing climate change

As climate change continues to pose significant challenges to agriculture, traditional knowledge offers valuable insights into climate adaptation and mitigation. Practices such as intercropping and mulching, which have been used for centuries, help conserve soil moisture, reduce erosion, and improve soil fertility, thereby contributing to climate resilience.[135,136] These traditional practices can be instrumental in developing adaptive strategies for changing climatic conditions.

6. Challenges and opportunities for integration

Integrating traditional knowledge with modern agricultural practices involves navigating various challenges while seizing opportunities for enhanced soil management. The coexistence of these approaches can lead to innovative solutions that balance cultural heritage with technological advancement, promoting sustainable agricultural practices.

6.1. Challenges

6.1.1. Knowledge erosion

One of the primary challenges is the erosion of traditional knowledge due to the increasing adoption of modern agricultural practices. As farming becomes more mechanized and reliant on chemical inputs, conventional techniques, such as crop rotation, organic manuring, and water conservation, are often overlooked.[137,138] This shift results in a decline in the transmission of traditional knowledge across generations. Younger farmers, influenced by modern methods and lacking exposure to conventional practices, may not learn or use these time-tested techniques, leading to a loss of valuable agronomic wisdom.[139]

6.1.2. Lack of documentation

Traditional knowledge is frequently passed down orally, which can lead to its eventual loss if not systematically documented.[140] The absence of written records or formal documentation makes it challenging to study, validate, and integrate traditional practices into contemporary agricultural systems. This lack of documentation hinders efforts to scientifically evaluate and adapt conventional methods for modern use, risking the loss of effective soil management strategies.[141]

6.1.3. Policy and institutional barriers

Agricultural policies and institutional frameworks often prioritize modern agricultural techniques over traditional practices, presenting a significant challenge.[25,142,143] Policies that favor large-scale, industrial agriculture may not adequately support or recognize the benefits of traditional practices, resulting in insufficient resources, incentives, or support for integrating traditional knowledge. In addition, research and development funds are frequently allocated to modern technologies rather than to studying and reviving traditional methods.[134]

6.2. Opportunities

6.2.1. Revival of traditional practices

There is substantial potential to revive and promote traditional soil management practices through dedicated initiatives. Documenting traditional knowledge through research and community engagement can help preserve and enhance these practices.[139,144] Collaborative efforts involving researchers, practitioners, and local communities can facilitate the recording and dissemination of traditional techniques, ensuring their continued relevance and application in modern agriculture.[139]

6.2.2. Integration with modern techniques

Combining traditional soil management practices with modern technologies presents a promising approach to enhancing soil health and agricultural sustainability. Integrative approaches can leverage the strengths of both traditional and modern methods to address contemporary agricultural challenges.[128,145] For example, integrating traditional water conservation techniques with modern irrigation technologies can optimize water use and enhance soil fertility.[127] Such synergies can lead to more sustainable and effective soil management strategies.

6.2.3. Community-based approaches

Engaging local communities in the planning and implementation of soil management strategies can ensure the effective integration of traditional knowledge. Community-based approaches that involve local knowledge holders can enhance the relevance and acceptance of soil management practices.[146,147] By fostering collaboration between communities, researchers, and policymakers, it is possible to develop strategies that honor traditional knowledge while addressing modern agricultural needs.

6.2.4. Policy and institutional support

Advocating for policy and institutional changes to support traditional practices is crucial for their integration with modern techniques. Policy reforms that recognize and incentivize the use of conventional knowledge can create a more inclusive agricultural system.[137,143] Providing financial and technical support for research on traditional practices and their integration with modern technologies can facilitate the broader adoption of these practices.

In summary, while integrating traditional knowledge with modern agricultural practices presents challenges, including knowledge erosion, a lack of documentation, and policy barriers, it also offers significant opportunities. Reviving traditional practices, combining them with modern technologies, and involving communities in the integration process can lead to more sustainable and resilient soil management strategies. Addressing these challenges and leveraging the opportunities can enhance the effectiveness and sustainability of agricultural systems.

7. Conclusion

Integrating traditional knowledge with modern agricultural practices offers a pathway to more sustainable and resilient soil management. Traditional practices, such as crop rotation, organic manuring, and water conservation techniques, have long demonstrated their effectiveness in maintaining soil health and productivity. However, the erosion of this knowledge, the lack of documentation, and policy barriers pose significant challenges to their integration with contemporary methods. To address these challenges, it is essential to revitalize and document traditional practices through collaborative efforts involving researchers, practitioners, and local communities. Integrating these practices with modern technologies can optimize soil management and enhance agricultural sustainability. Policymakers should support this integration by developing inclusive policies that recognize and incentivize traditional practices. Future research should focus on the practical applications of combined approaches and their impacts on soil health and productivity. By bridging traditional and modern practices, we can foster a more holistic approach to soil management that benefits both agriculture and the environment.

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Author contributions

Conceptualization: Himanshu Sahu, Pooja Purohit, Arun Pratap Mishra
Investigation: Himanshu Sahu, Pooja Purohit, Arun Pratap Mishra
Methodology: Himanshu Sahu, Pooja Purohit, Arun Pratap Mishra, Amit Kumar
Writing – original draft: Himanshu Sahu, Pooja Purohit, Arun Pratap Mishra, Amit Kumar, Purnendu Sardar
Writing – review & editing: All authors

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