PLANT SCIENCE TODAY
Vol 12(sp3): 01–09
https://doi.org/10.14719/pst.8263

eISSN 2348-1900

REVIEW ARTICLE

Exploring soil dynamics, microbial life and nutrient cycling in non-puddled rice: A comparative study

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Received: 14 March 2025; Accepted: 16 May 2025; Available online: Version 1.0: 23 June 2025

Cite this article: Abarajitha P, Subrahmaniyan K, Elamathi1 S, Manimaran R, Manikandan K, Sivasankari Devi T, Hariniharishma VP. Exploring soil dynamics, microbial life and nutrient cycling in non-puddled rice: A comparative stud. Plant Science Today. 2025;12(sp3):01–09. https:/doi.org/10.14719/pst.8263

Abstract

Non-puddled rice cultivation is gaining traction as a sustainable alternative to traditional puddled transplanting, particularly due to its potential to enhance soil health, nutrient use efficiency and mitigate environmental impacts. This review synthesizes recent findings from studies conducted in India and other rice-growing nations, comparing the effects of non-puddled and puddled systems on key soil properties and processes. Evidence suggests that non-puddled rice cultivation generally leads to improved soil physical properties, including increased porosity and reduced bulk density, facilitating better water infiltration and root development. These changes promote beneficial soil biota activity, enhancing nutrient cycling and availability. Consequently, non-puddled systems often exhibit higher nitrogen use efficiency by 15-20 % and phosphorus use efficiency 10-20 % thereby reducing losses and increasing overall nutrient use efficiency which further influenced to reduced fertilizer requirement. Non-puddled rice systems increase water productivity by improving soil structure and water infiltration. This enhances root growth, allowing plants to access more water. Reduced percolation and seepage losses, along with efficient water use by plants, further contribute to higher productivity. Non-puddled systems also facilitate alternate wetting and drying irrigation, reducing water consumption efficiency compared to puddled transplanted rice. Nutrient and water use efficiency, requiring lower fertilizer inputs and water, while achieving comparable or even higher yields compared to puddled rice with respect to soil physical and biological characteristics. Furthermore, the reduced flooding associated with non-puddling significantly lowers methane emissions, a potent greenhouse gas. This review highlights the potential of non-puddled rice cultivation to contribute more sustainable and resilient rice production systems while addressing pressing environmental concerns.

Keywords: beneficial soil biota; non-puddled rice; nutrient use efficiency; soil health; sustainable agriculture

Introduction

Rice (*Oryza sativa* L.) is a staple crop for global food security, with rice cropping systems providing essential ecosystem services like nutrient cycling and carbon sequestration (1). However, rice-rice cropping systems often suffer reduced productivity due to soil quality degradation caused by continuous submergence, imbalanced fertilization and inadequate organic carbon recycling (2). Puddling of soil also consumes 200-250 mm of water, equivalent to 17 % of the total water used by rice (3). This significant water consumption underscores the importance of efficient soil management practices in rice cultivation. To address this issue, there is growing interest in alternative rice establishment methods, particularly non-puddled cultivation, which seems promising for improving soil health and productivity in rice-based cropping systems (4). By minimizing water usage by 10-15 % compared to traditional transplanted rice and reducing soil disturbance, the non-puddled method maintains soil structure and promotes the activity of beneficial microorganisms (5). Furthermore, it enables better oxygenation of the root zone, leading to an improvement in nutrient uptake and crop growth. Non-puddled systems were also observed to enhance the resilience of rice crops to climate variability, particularly in areas prone to drought or erratic rainfall patterns (6). This review article aims to compare the changes in soil physical properties, soil biota and nutrient transformation in non-puddled and puddled rice cultivation systems

Soil, water and nutrient dynamics in non-puddled rice systems

Puddling was classified according to the quality, based on change in apparent specific volume of the silty clay soil and availability of the soil moisture, as follows, granulated, paste ΔASV = 0.06-0.09 $cm^3 g^{-1}$) and muddy. The ΔASV of the silty clay soil was dependent on cropping system, crop residue management and method of land preparation for rice (7). However, in non-puddled systems, the soil is not subjected to intensive mechanical disturbance, which allows the natural soil structure to be maintained that deviates from the traditional method (4). The breakdown is, that traditional puddling involves tilling the soil with standing water to create a soft, muddled seedbed. While this facilitates transplanting and initially controls weeds, it leads to, destruction of soil structure and formation of hard pans, creates anaerobic conditions by limited oxygen availability, impacts nutrient cycling and beneficial soil organisms, increases water use that leads to higher evaporation and percolation losses (8). Non-puddling aims to minimize or eliminate these drawbacks by either reduced or zero tillage, moist or dry seedbed preparation and controlled irrigation (9).

Key features of non-puddling (10)

Better soil health is achieved through better aeration, drainage and enhanced microbial activity, which creates a more conducive environment for plant growth. This leads to water conservation resulting in lower water requirements. Additionally, nutrient use efficiency is improved, with potentially higher nutrient availability and reduced nutrient losses. These practices also offer environmental benefits, such as lower greenhouse gas emissions and a reduction in water pollution, contributing to a more sustainable agricultural system.

Variations in non-puddling (11)

Direct seeding involves sowing seeds directly into the field without the need for transplanting, offering a more efficient approach to rice cultivation. The System of rice intensification (SRI) incorporates a set of specific practices that combine non -puddling with other management techniques. Non-puddling, a key aspect of SRI, represents a shift towards more sustainable rice farming by enhancing soil health, promoting water conservation and improving nutrient use efficiency. This method not only benefits the environment but also supports more sustainable agricultural practices.

Soil physical properties - non-puddling vs. puddling in rice cultivation

Soil physical properties play a crucial role in conserving the overall health and productivity of agricultural systems, particularly in rice cultivation (12). The adoption of non-puddled rice cultivation techniques significantly influences the soil physical properties, which in turn had impact on water and nutrient dynamics, as well as the overall performance of the rice crop (13). Puddling is the destruction of soil structure, leading to the formation of a hard pan (14). This compaction reduces soil aeration, limits the root growth and impedes the water infiltration, which ultimately affects the availability of water and nutrients to the crop. In contrast, non-puddled systems such as reduced or zero tillage helps to preserve soil structure and maintain the optimal physical conditions (15).

Soil structure and aggregation

Transplanted puddled rice leads to the breakdown of soil aggregates, resulting in a compact soil structure (16). In contrast, non-puddled rice systems often exhibit improved soil structure and aggregation, as the soil is not subjected to the intensive disturbance associated with puddling (17). The maintenance of soil aggregation in non-puddled systems could enhance soil aeration, water infiltration and root growth, which are essential for the optimal growth and development of rice plants. Non-puddled rice systems had higher soil aggregate stability and a greater proportion of macro-aggregates compared to puddled systems (18). This improved soil structure was attributed to the reduced physical disturbance and the increased presence of soil biota such as earthworms, which contribute to the formation and stabilization of soil stable aggregates, which could be improved water in soil aggregates of 1.2 mm and 1.8 mm in puddled and non-puddled soil respectively. This indicates that non-puddled soils generally have larger, more stable soil aggregates compared to puddled soils. Non-puddled systems exhibited a higher proportion of water-stable aggregates, which could also improve soil water-holding capacity and reduce the risk of soil erosion (19).

Aggregate stability

Non-puddled systems promote better aggregation due to reduced soil disturbance, enhanced organic matter content with an average of 18.4 g kg^{-1}, compared to puddled systems, which had an average of 15.8 g kg^{-1} and combined with residue retention, led to a 15 % increase in microbial biomass carbon and a 22 % increase in microbial biomass nitrogen compared to conventional puddling in a rice-wheat cropping system (20). Aggregate stability in non-puddled soils was reported to be 10-30 % higher than that of puddled condition (20). The mean weight diameter (MWD) of soil aggregates, a measure of stability, was 1.8 mm under non-puddling as compared to 1.2 mm under puddling through natural processes that lead to the formation of stable soil aggregates. This results in a higher MWD, indicating better soil structure, improved water infiltration, enhanced aeration and increased resistance to erosion (21). Conversion from puddled to non-puddled rice cultivation led to a 15 % increase in water-stable aggregates and a 10 % decrease in soil bulk density (22). While puddling disrupts soil aggregates by creating a compact soil layer with high bulk density and low porosity. This leads to poor aeration, reduced water infiltration and increased susceptibility to erosion resulting in a decrease in aggregate stability by 20-50 % (23).

Pore size distribution

Non-puddled systems have the more balanced pore size distribution, with a higher proportion of macro-pores, which are crucial for drainage and aeration and micro-pores that is important for water retention. It could increase macro-porosity by 10-20 % and total porosity by 5-15 % (20). However, puddling destroys macro-pores, leading to a higher proportion of micro-pores and reduced overall porosity. This results in poor drainage, waterlogging and anaerobic conditions (24).

Soil compaction

Non-puddling reduced the soil penetration resistance by 10-30 % when compared to puddling (25). Penetration resistance at a depth of 10 cm was 1.5 MPa under non-puddling as compared to 2.2 MPa under puddling (26). Direct-seeded rice in non-puddled systems had 20 % higher root biomass and 30 % deeper root penetration compared to transplanted rice in puddled systems (18).

Soil bulk density

Puddling of soil for rice cultivation can lead to the compaction of the soil, resulting in increased bulk density and reduced porosity. In contrary, non-puddled rice systems often exhibit lower bulk density (5-15 %) and higher porosity, which could enhance water infiltration, gas exchange and root penetration (25, 27). The maintenance of desirable soil physical properties, such as low bulk density and high porosity, in non-puddled rice systems can contribute to improved water-use efficiency, nutrient uptake and overall crop performance (28). Non-puddling reduced bulk density from 1.5 g cm^{-3} to 1.3 g cm^{-3} in a loam soil, which significantly improved the root penetration (29). In comparison to non-puddled soil, puddling increased the bulk density from 1.1 g cm^{-3} to 1.4 g cm^{-3} in a clay loam soil (30).

Soil porosity

Enhanced aggregation and reduced compaction in non-puddled systems create a more favorable pore size distribution, with a higher proportion of macro-pores essential for drainage and aeration. Non-puddling increased the total porosity by 5-15 % and macro-porosity by 10-20 % (30, 31) over transplanted puddled rice cultivation. In silty clay loam soil, non-puddling increased the total porosity from 45 % to 52 % and macro-porosity from 10 % to 18 % compared to puddling. Puddling reduced the total porosity from 55 % to 48 % and macro-porosity from 20 % to 8 % in paddy soil, negatively impacting the water infiltration and aeration (32).

Aeration porosity

Non-puddled systems significantly increased the higher aeration porosity, particularly in the root zone, which is crucial for root respiration. Aeration porosity can be 2-3 times higher in non-puddled soils, especially during the active tillering stages of rice growth. However, key considerations will be the type of soil, puddling intensity and management practices like residue incorporation and crop rotations (33).

Soil hydraulic properties

The adoption of non-puddled rice cultivation had significant impacts on soil hydraulic properties, such as infiltration rate, permeability and water-holding capacity (19). Non-puddled rice systems had higher saturated hydraulic conductivity compared to puddled systems, indicating improved water movement and reduced risk of waterlogging (31). Additionally, non-puddled systems were reported to have higher water-holding capacity, which can be beneficial during periods of water scarcity and help mitigate the impacts of drought on rice production (34). The improvements in soil hydraulic properties under non-puddled rice cultivation could contribute to more efficient water use, reduced irrigation requirements and enhanced water availability for plant growth and development (13).

Non-puddled systems consistently exhibit higher infiltration rates across all soil types compared to puddled systems (Table 1). This has been attributed to the improved soil structure, reduced compaction and the presence of macro-pores (25). Like the infiltration rate, Ksat is generally higher in non-puddled systems due to better water movement through the soil profile (38). Higher water holding capacity, particularly in clayey soils, due to the creation of a puddled layer, which retains more water would also lead to waterlogging if drainage is poor (39). However, this could vary significantly depending on specific soil properties, puddling intensity, management practices and environmental factors considered as important factors.

Soil compaction

Penetration resistance, a measure of soil compaction, is often significantly lower in non-puddled soils, particularly in the top 15 cm of the soil profile (40). Non-puddled systems with lower compaction risk due to reduced soil disturbance that minimizes soil manipulation, preserving natural soil structure and reducing compaction from machinery (31). Enhanced organic matter decomposition in non-puddled systems improves the soil structure and reduces the susceptibility to compaction (41). However, pose a higher risk of compaction under-transplanted puddled rice field, forming a compacted soil layer resulting low porosity and with poor drainage, restricting root growth and water infiltration (42, 43).

Erosion risks

Non-puddled systems had a higher initial erosion risk due to the absence of standing water, which leaves the soil surface more vulnerable to rainfall impact and runoff (44). While detrimental to other soil properties, the puddled layer could act as a barrier to erosion (25, 45). The breakdown of soil structure in puddled systems can make the soil more susceptible to erosion during subsequent crops or after heavy rainfall (46).

Mitigating erosion in non-puddled systems (47)

Residue retention : Leaving crop residues on the soil surface protects the soil from rainfall impact and reduces runoff

Table 1. Comparison of soil hydraulic properties in puddled and non-puddled system

Soil hydraulic property	Soil Type	Puddled system	Non- puddled system	Reference
Infiltration rate (cm/ hr)	Clayey	0.5 - 1.5	1.5-3.0	(35)
	Loamy	1.0 - 2.5	2.5 - 5.0	
	Sandy	2.0 - 4.0	4.0-7.0	
Saturated hydraulic conductivity (cm/ hr)	Clayey	0.1 - 0.5	0.5 - 1.5	(36)
	Loamy	0.5 - 1.5	1.5-3.0	
	Sandy	1.0-2.5	2.5-5.0	
Water holding capacity (%)	Clayey	45-55	40-50	(37)
	Loamy	40-50	35-45	
	Sandy	30-40	25-35	

velocity.

Cover crops : Planting cover crops during fallow periods helps improve soil structure, increase organic matter and prevent soil erosion.

Conservation tillage : Minimizing soil disturbance through reduced tillage practices further protects the soil from erosion. However, the soil type influenced by soil texture, soil slope, rainfall patterns, topography and long-term impacts are the key considerations.

Soil type considerations : The effectiveness of erosion control strategies is influenced by soil texture, slope and topography, all of which affect water infiltration and runoff.

Long term impacts : Sustainable erosion control requires consideration of long term impacts on soil health, ensuring that practices contribute to the ongoing fertility and stability of the soil.

Influence of non-puddling on microbial biomass in rice systems

Microbial biomass serves as a key indicator of soil health, reflecting the total mass of living microorganisms like bacteria and fungi present in the soil (48). Non-puddled rice cultivation consistently demonstrates a positive influence on microbial biomass compared to puddling systems. This is attributed to improved soil aeration, enhanced organic matter decomposition and a more favourable environment for microbial growth (49). Puddled rice cultivation disrupts the soil microbial community, leading to a reduction in the diversity and abundance of beneficial microorganisms (1). In contrast, non-puddled rice systems often exhibit a more diverse and active soil microbial community, as the reduced soil disturbance promotes the establishment and proliferation of a wide range of microorganisms (50). Furthermore, non-puddled rice systems had nitrogen-fixing bacteria, such as *Azospirillum* and *Azotobacter* abundantly, which enhances the availability of nitrogen for plant uptake and reduces the reliance on synthetic fertilizers (51). Also showed a higher diversity and abundance of beneficial soil microorganisms, such as nitrogen-fixing bacteria and phosphate-solubilizing bacteria, with an average population of 2.8×10^{7} CFU g^{-1} and 1.6×10^{6} CFU g^{-1} respectively, compared to the puddled system, which had an average population of 1.9×10^{7} CFU g^{-1} and 1.1×10^{6} CFU g^{-1} respectively (52). Non-puddled system significantly resulted in higher abundance and diversity of beneficial soil microorganisms such as nitrogen-fixing bacteria and phosphate-solubilizing fungi, with an average population of 3.1×10^{7} CFU g^{-1} and 2.4×10^{5} CFU g^{-1} respectively, compared to the puddled system, which had an average population of 2.2×10^{7} CFU g^{-1} and 1.8×10^{5} CFU g^{-1} respectively (53).

The increase in microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) in non-puddled systems typically ranges from 10-30 % compared to puddled counterparts by improving soil aeration and reduced soil disturbance in non-puddled systems (54). Non-puddled rice cultivation, combined with residue retention, led to a 15 % increase in MBC and 22 % increase in MBN compared to conventional puddling in rice-wheat cropping system with positive effects on soil carbon sequestration (55). On long term study observed that continuous non-puddled rice cultivation resulted in significantly higher MBC and MBN compared to puddled systems resulted in 25 % increase in MBC after ten years of non-puddled management. It emphasizes the sustained positive impacts of non-puddling on microbial biomass over time, contributing to improved soil health and fertility (47).

Enzyme activity

Enzyme activity is a sensitive indicator of soil biological health and nutrient cycling potential. Non-puddled rice cultivation generally enhances enzyme activity compared to puddled systems, primarily due to improved aeration, better drainage and enhanced organic matter decomposition (56).

β-glucosidase

Non-puddled systems exhibit 10-30 % higher β-glucosidase activity compared to puddled systems (57). In non-puddled rice cultivation, combined with residue retention led to a 25 % increase in β-glucosidase activity that breaks down cellulose, a major component of plant residues, releasing glucose for microbial use and contributing to soil organic matter formation compared to conventional puddling. This increase was attributed to improved soil aeration and greater availability of organic matter for decomposition (58).

Phosphatase

Non-puddled systems resulted in 20-50 % higher phosphatase activity compared to puddled systems. Even though, non-puddled rice cultivation can enhance both acid and alkaline phosphatase activities by 15-35 % compared to puddled systems. This is due to the improved availability of organic phosphorus substrates, better soil aeration and a more favorable pH range for phosphatase enzyme production and activity (56). Non-puddled rice systems exhibited 30 % higher phosphatase activity, which releases phosphorus from organic matter, making it available for plant uptake compared to puddled systems. This increase is attributed to enhanced microbial activity and improved phosphorus cycling in non-puddled soils (59).

Urease

Non-puddled systems demonstrate 15-40 % higher urease activity, that converts urea, a common nitrogen fertilizer, into ammonia in a plant available form of nitrogen than the puddled systems due to improved soil structure and greater microbial abundance. Also noted that urease activity was 25 % higher in non-puddled treatments compared to puddled treatments, which can lead to improved nitrogen use efficiency in rice production, reducing nitrogen losses (60).

Beneficial organisms

Earthworm abundance: Non-puddled systems typically support significantly larger earthworm populations due to improved aeration. Non-puddled soils have better oxygen availability, which is essential for earthworm survival and activity. It enhances drainage by reducing waterlogging in non-puddled systems to prevent earthworms drowning and creates more suitable habitats. Non-puddled systems often exhibit 2-3 times greater earthworm density compared to puddled fields (61). A 2.5-fold increase in earthworm density in non-puddled rice compared to puddled rice. This increase

Table 2. Comparative analysis of rice yields in puddled and non-puddled system

Characteristics	Puddled system	Non-puddled system	Effects	References
Water productivity	0.45 kg/m^3	0.68 kg/m^3	The improved water productivity and higher yields in the non-puddled system were attributed to the enhanced soil physical properties such as increased porosity and reduced bulk density, which facilitated better water infiltration, root growth and nutrient uptake by the rice plants.	(75)
Yield	4.9 t/ ha	5.8 t/ ha		
Soil organic carbon content	18.4 g/ kg	15.8 g/ kg	The improved soil physical properties in the non-puddled system led to higher rice yields.	(76)
Soil porosity	48 %	52 %		
Yield	5.6 t/ ha	6.2 t/ ha		

was attributed to improved soil physical properties and greater availability of organic matter in the non-puddled system (62).

Mycorrhizal fungi colonization : Non-puddling promotes the growth and colonization of mycorrhizal fungi, which forms beneficial associations with plant roots, enhancing nutrient and water uptake by 15 % increase in mycorrhizal colonization of rice roots (63).

Detrimental organisms

Methane producing archaea - Puddling creates anaerobic conditions that favours the methane producing microorganisms, contributing to greenhouse gas emissions. Non-puddling mitigates greenhouse gases (GHG) by reducing the methane emissions by 20-30 % compared to puddled rice production system (64).

Nutrient transformation and availability - non-puddled vs. puddled rice systems

The changes in soil physical properties and soil biota in non-puddled rice cultivation can also influence the transformation and availability of essential plant nutrients such as nitrogen, phosphorus and potassium (65).

Nitrogen (N) dynamics

Puddling creates anaerobic conditions, promoting denitrification, a process that converts nitrate (NO^{3-}) into nitrogen gas (N_2), leading to significant N loss from the soil (66). Improved aeration in non-puddled systems reduce denitrification losses, promoting greater N retention in the soil with higher N use efficiency, exhibiting 10-20 %, which utilizes N more effectively from the soil (67). It also enhances microbial activity, leading to faster decomposition of organic matter and greater release of plant-available nitrogen (ammonium, NH^{4+}) with higher nitrogen uptake of 15 % (68).

Phosphorus (P) availability

In puddled conditions, iron and aluminum oxides become more soluble, leading to increased P fixation, making them less available to plants (18). Aerobic conditions in non-puddled systems reduce P fixation, making it more accessible to plants and resulting in 15-30 % higher P use efficiency (69). Greater microbial activity in non-puddled soils enhances the mineralization of organic P, further increasing its availability, attributed to 20 % higher P uptake compared to puddled rice, linked to reduced fixation and enhanced mobilization (70).

Other nutrients

Non-puddled systems generally exhibit better potassium availability due to improved soil structure and enhanced nutrient cycling (71). The availability of micronutrients like zinc and iron can also be enhanced in non-puddled systems due to improved soil aeration and microbial activity (23). However, regular soil testing is crucial to monitor nutrient levels and adjust fertilizer application accordingly in both puddled and non-puddled rice production systems.

Overall nutrient use efficiency

A meta-analysis in non-puddled rice systems had improved the nutrient cycling and reduced losses contributing to a higher N use efficiency of 15-25 % and 10-20 % higher P use efficiency compared to puddled systems also influences the lesser N and P requirement of 10-15 % and 5-10 % respectively to achieve similar yields compared to puddled rice (72).

Impact on fertilizer requirements

Non-puddled systems often require lower fertilizer inputs to achieve comparable yields to puddled systems. This is due to improved nutrient use efficiency and reduced losses (72).

Environmental implications

Non-puddled systems generally have a lower environmental footprint compared to puddled systems due to lower methane emissions from reduced flooding ranging from 20-70 % or even higher, depending on specific practices and environmental conditions. This reduction is a major advantage, as methane is a potent greenhouse gas with a much higher global warming potential than carbon dioxide (73). Less N and P leaching into water bodies, minimizing water pollution and eutrophication (74).

Future perspective

Assessing the long-term effects of non-puddled rice cultivation on soil health, nutrient dynamics and greenhouse gas emissions in diverse agro-ecosystems.

Investigating the interactions between soil biota, nutrient cycling and plant growth in non-puddled systems to identify the key drivers of improved productivity.

Exploring the potential of integrating non-puddled rice cultivation with other sustainable agricultural practices, such as organic amendments, cover cropping and integrated pest management to enhance overall system sustainability.

Non-puddled rice systems are more prone to weed infestation, leading to increased competition for nutrients and potential nutrient loss. Effective weed management practices like mechanical weeding, mulching and herbicides are necessary. While non-puddling offers benefits, proper weed control is essential for optimizing yields and soil health.

Ultimately, the adoption of non-puddled rice cultivation systems has the potential to contribute to more sustainable and resilient rice production systems, also addressing environmental concerns related to soil degradation and greenhouse gas emissions.

Conclusion

The transition from puddled rice cultivation to non-puddled systems represents a significant shift towards a more sustainable and resilient rice production system. This comparative analysis has highlighted how non-puddling fosters a cascade of positive changes, beginning with enhanced soil physical properties viz., increased porosity and reduced bulk density. These improvements create a favourable environment for beneficial soil biota, leading to greater microbial activity and more efficient nutrient cycling. Consequently, non-puddled rice cultivation often demonstrates higher nutrient use efficiency, reduced fertilizer requirements and minimized environmental impacts compared to its puddled system. While further research is crucial to optimize management practices and address region-specific challenges, the evidence strongly suggests that the widespread adoption of non-puddled rice cultivation holds immense promise for promoting both agricultural productivity and environmental sustainability in global rice production.

Acknowledgements

The author gratefully acknowledges the support and encouragement provided by Tamil Nadu Rice Research Institute (TRRI), Aduthurai throughout the development of this article. Special thanks are extended to the Chairman-Director [TRRI] for his valuable insights and guidance.

Authors' contributions

PA conceptualized the review and prepared the initial draft. KS reviewed and corrected the structural framework of the article. SE ensured the accuracy and relevance of cited literature. RM refined the methodology and technical details discussed. KM corrected grammatical and linguistic errors. TSD enhanced the coherence and flow of the manuscript. VPH performed the final proofreading and formatting for submission.

Compliance with ethical standards

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical issues: None

References

1. Chaudhary A, Venkatramanan V, Mishra AK, Sharma S. Agronomic and environmental determinants of direct seeded rice in South Asia. Circular Economy and Sustainability. 2022;3(1):253-90. https://doi.org/10.1007/s43615-022-00173-x.
2. Salahin N, Jahiruddin M, Islam MR, Alam MK, Haque ME, Ahmed S, et al. Establishment of crops under minimal soil disturbance and crop residue retention in rice-based cropping system: yield advantage, soil health improvement and economic benefit. land. 2021;10(6):581. https://doi.org/10.3390/land10060581.
3. Shrestha S, Shrestha J, Jha SK, Khadka D, Paneru P, Gyawaly P. Soil chemical properties under conservation agriculture and cereal-based cropping system in eastern Tarai of Nepal. Journal of Nepal Agricultural Research Council. 2020;6:115-26. https://doi.org/10.3126/jnarc.v6i0.28122.
4. Saha S, Munda S, Singh S, Kumar V, Jangde HK, Mahapatra A, et al. Crop establishment and weed control options for sustaining dry direct seeded rice production in Eastern India. Agronomy. 2021;11(2):389. https://doi.org/10.3390/agronomy11020389.
5. Zhao C, Chen M, Li X, Dai Q, Xu K, Guo B, et al. Effects of soil types and irrigation modes on rice root morphophysiological traits and grain quality. Agronomy. 2021;11(1):120. https://doi.org/10.3390/agronomy11010120.
6. Panda S, Majhi PK, Anandan A, Mahender A, Sumanth V, Bastia DK, et al. Proofing direct-seeded rice with better root plasticity and architecture. International Journal of Molecular Sciences. 2021;22(11):6058. https://doi.org/10.3390/ijms22116058.
7. Tsubo M, Fukai S, Basnayake J, Tuong TP, Bouman B, Harnpichitvitaya D. Effects of soil clay content on water balance and productivity in rainfed lowland rice ecosystem in Northeast Thailand. Plant Production Science. 2007;10(2):232-41. https://doi.org/10.1626/pps.10.232.
8. Sahu K, Pasupalak S, Diwan UK. Evaluation of water use efficiency of rice genotypes under different rice establishment methods and different growing environment. International Journal of Current Microbiology and Applied Sciences. 2018;7(1):2534-8. https://doi.org/10.20546/ijcmas.2018.701.304.
9. Alam MK, Bell RW, Hasanuzzaman M, Salahin N, Rashid MH, Akter N, et al. Rice (*Oryza sativa* L.) establishment techniques and their implications for soil properties, global warming potential mitigation and crop yields. Agronomy. 2020;10(6):888. https://doi.org/10.3390/agronomy10060888.
10. Alori ET, Glick BR, Babalola OO. Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Frontiers in Microbiology. 2017;8:971 https://doi.org/10.3389/fmicb.2017.00971
11. Abduljaleel Y, Demissie Y. Evaluation and optimization of low impact development designs for sustainable stormwater management in a changing climate. Water. 2021;13(20):2889. https://doi.org/10.3390/w13202889
12. Hossain MA, Rana MM, Al-Rabbi SH, Mitsui T. Management of puddled soil through organic amendments for post-rice mungbean. Asian Journal of Agriculture and Biology. 2021;2021(1):1-11. https://doi.org/10.35495/ajab.2020.04.255
13. Subrahmaniyan K, Rajavel M, Veeramani P, Parthipan T. Tillage practices on soil penetration resistance, soil infiltration, percolation and yield of rice (*Oryza sativa*) in rice-based cropping system. The Indian Journal of Agricultural Sciences. 2024;94:811. https://doi.org/10.56093/ijas.v94i8.145235
14. Fujihara Y, Yamada R, Oda M, Fujii H, Ito O, Kashiwagi J. Effects of puddling on percolation and rice yields in rainfed lowland paddy cultivation: Case study in Khammouane province, central Laos. Agricultural Sciences. 2013;4(8):360-8.

https://doi.org/10.4236/as.2013.48052

15. Rahman A, Amin MM. Soil hydraulic properties and field-scale hydrology as affected by land-management options. Sains Tanah - Journal of Soil Science and Agroclimatology. 2023;20(1):124-39. https://doi.org/10.20961/stjssa.v20i1.70504
16. Zhang ZB, Zhou H, Lin H, Peng X. Puddling intensity, sesquioxide and soil organic carbon impacts on crack patterns of two paddy soils. Geoderma . 2016;262:155-64. https://doi.org/10.1016/j.geoderma.2015.08.030
17. Arunrat N, Kongsurakan P, Sereenonchai S, Hatano R. Soil organic carbon in sandy paddy fields of northeast Thailand: A Review. Agronomy. 2020;10(8):1061. https://doi.org/10.3390/agronomy10081061.
18. Kirchhof G, So HB. Soil puddling for rice production under glasshouse conditions-its quantification and effect on soil physical properties. Soil Research. 2005;43(5):617-22. https://doi.org/10.1071/SR04068
19. Woldemariam WG, Ghoshal N. Microbial community, biomass and physico-chemical properties of soil in dry tropics. Preprint (Version 1) available at Research Square . 2020. https://doi.org/10.21203/rs.3.rs-36821/v1
20. Nelson KA, Motavalli PP. Nitrogen source, drainage and irrigation affects corn yield response in a claypan soil. Applied Engineering in Agriculture. 2013;29(6):875-84. https://doi.org/10.13031/aea.29.9809
21. Yadav S, Evangelista GK, Faronilo J, Humphreys E, Yamauchi A, Fernandez L. Establishment method effects on crop performance and water productivity of irrigated rice in the tropics. Field Crops Research. 2014;166:112-27. https://doi.org/10.1016/j.fcr.2014.06.001
22. Harun NS, Hanafiah MM, Nizam NU, Rasool A. Water and soil physicochemical characteristics of different rice cultivation areas. Applied Ecology and Environmental Research. 2020;18(5):6775. https://doi.org/10.15666/aeer/1805_67756791
23. Venkataravana Nayaka GV, Prabhakara Reddy G, Mahender Kumar R. Performance of rice under different systems of cultivation: A Review. Indian Journal of Pure & Applied Biosciences. 2020;8(4):612-30. https://doi.org/10.18782/2582-2845.8204
24. Kukal SS, Aggarwal G. Percolation losses of water in relation to puddling intensity and depth in a sandy loam rice (*Oryza sativa*) field. Agricultural Water Management. 2002;57(1):49-59. https://doi.org/10.1016/s0378-3774(02)00037-9
25. Paul PL, Bell RW, Barrett-Lennard EG, Kabir E. Impact of rice straw mulch on soil physical properties, sunflower root distribution and yield in a salt-affected clay-textured soil. Agriculture. 2021;11(3):264. https://doi.org/10.3390/agriculture11030264
26. Devkota KP, Yadav S, Khanda C, Beebout SJ, Mohapatra BK, Singleton GR, et al. Assessing alternative crop establishment methods with a sustainability lens in rice production systems of Eastern India. Journal of Cleaner Production. 2020;244:118835. https://doi.org/10.1016/j.jclepro.2019.118835
27. Han Z, Li J, Gao P, Huang B, Ni J, Wei C. Determining the shear strength and permeability of soils for engineering of new paddy field construction in a hilly mountainous region of southwestern China. International Journal of Environmental Research and Public Health. 2020;17(5):1555. https://doi.org/10.3390/ijerph17051555
28. Horn R, Taubner H, Wuttke MW, Baumgartl T. Soil physical properties related to soil structure. Soil and Tillage Research. 1994;30(2-4):187-216. https://doi.org/10.1016/0167-1987(94)90005-1
29. Liu J, Wang Z, Li Y. Efficacy of natural polymer derivatives on soil physical properties and erosion on an experimental loess hillslope. International Journal of Environmental Research and Public Health. 2017;15(1):9. https://doi.org/10.3390/ijerph15010009
30. Adebowale AA, Sanni LO, Owo HO, Karim OR. Effect of variety and moisture content on some engineering properties of paddy rice. Journal of Food Science and Technology. 2010;48:551-9. https://doi.org/10.1007/s13197-010-0173-3
31. Singh KB. Dynamics of hydraulic properties of puddled soils. In: Elango L, editor. Hydraulic conductivity-issues, determination and applications. London: IntechOpen Limited; 2011. p. 29-46. https://doi.org/10.5772/17531
32. Ding X, Liang X, Zhang Y, Fang Y, Zhou J, Kang T. Capillary water absorption and micro pore connectivity of concrete with fractal analysis. Crystals. 2020;10(10):892. https://doi.org/10.3390/cryst10100892
33. Zhang ZB, Zhou H, Lin H, Peng X. Puddling intensity, sesquioxides and soil organic carbon impacts on crack patterns of two paddy soils. Geoderma. 2016;262:155. https://doi.org/10.1016/j.geoderma.2015.08.030
34. Kumar N, Chhokar RS, Meena RP, Kharub AS, Gill SC, Tripathi SC, et al. Challenges and opportunities in productivity and sustainability of rice cultivation system: a critical review in Indian perspective. Cereal Research Communications. 2022;50:573-601. https://doi.org/10.1007/s42976-021-00214-5
35. Prasanthkumar K, Kumar MS, Gunasekar JJ, Sivakumar S, Masilamani P. Comparative evaluation of puddling techniques in sandy loam soil. Current Journal of Applied Science and Technology. 2019:38:1-5. https://doi.org/10.9734/cjast/2019/v38i630474
36. Zheng K, Cheng J, Xia J, Liu G, Lei X. Effects of soil bulk density and moisture content on the physico-mechanical properties of paddy soil in plough layer. Water. 2021;13(16):2290. https://doi.org/10.3390/w13162290
37. Perreault S, El Alem A, Chokmani K, Cambouris AN. Development of pedo transfer functions to predict soil physical properties in Southern Quebec (Canada). Agronomy. 2022;12(2):526. https://doi.org/10.3390/agronomy12020526
38. Deng C, Teng X, Peng X, Zhang B. Effects of simulated puddling intensity and pre-drying on shrinkage capacity of a paddy soil under long-term fertilization. Soil and Tillage Research. 2014;140:135-43. https://doi.org/10.1016/j.still.2014.02.012
39. Oo AZ, Sudo S, Inubushi K, Chellappan U , Yamamoto A, Ono K, et al. Mitigation potential and yield-scaled global warming potential of early-season drainage from a rice paddy in Tamil Nadu, India. Agronomy. 2018;8(10):202. https://doi.org/10.3390/agronomy8100202
40. Meena GK, Gulati IJ, Yadav SR, Kherawat BS, Singh C. Characterization of soils properties of irrigated fields of Bilara tehsil of Jodhpur district. International Journal of Chemical Studies. 2020;8(4):2195-201. https://doi.org/10.22271/chemi.2020.v8.i4x.9955
41. Subrahmaniyan K, Rajavel M, Veeramani P, Parthipan T. Tillage practices on soil penetration resistance, soil infiltration, percolation and yield of rice (*Oryza sativa*) in rice-based cropping system. The Indian Journal of Agricultural Sciences. 2024;94:811. https://doi.org/10.56093/ijas.v94i8.145235.
42. Báťková K, Miháliková M, Matula S. Hydraulic properties of a cultivated soil in temperate continental climate determined by mini disk infiltrometer. Water. 2020;12(3):843. https://doi.org/10.3390/w12030843
43. Yassine AM, Abdellah EA, Khalid NI. Evaluation of the compaction of a no-till vertisol field using methods of cone index and pedo-transfer function in semi-arid context of Morocco. Journal of Agricultural Science and Technology. 2019;9:141-50. https://doi.org/10.17265/2161-6256/2019.03.001
44. Williams JD, Reardon CL, Wuest SB, Long DS. Soil wet aggregate

stability in dryland pacific northwest intensified crop rotations. Soil Science Society of America Journal. 2018;82(2):455-62. https://doi.org/10.2136/sssaj2017.08.0302

45. Daigh AL, Bly A. Compaction Reaction: Soil compaction and ruts following a wet harvest. Crops & Soils 2020;53(3):24-8. https://doi.org/10.1002/crso.20029

46. Galaviz-González JR, Rangel J, Limón-Covarrubias P, Avalos D, Cabello-Suárez LY, López-Lara T, et al. Elastoplastic coupled model of saturated soil consolidation under effective stress. Water. 2022;14:2958. https://doi.org/10.3390/w14192958

47. Selbig WR, Buer NH. Hydraulic, water-quality and temperature performance of three types of permeable pavement under high sediment loading conditions. Scientific Investigations Report. 2018. https://doi.org/10.3133/sir20185037

48. Wang ShanShan WS, Sun BaoYang SB, Li ChaoDong LC, Li ZhanBin LZ, Ma Bo MB. Runoff and soil erosion on slope cropland: A review. Journal of Resources and Ecology. 2018;9(5):461-70. https://doi.org/10.5814/j.issn.1674-764x.2018.05.002

49. Tsegaye B. Effect of land use and land cover changes on soil erosion in Ethiopia. International Journal of Agricultural Science and Food Technology. 2019;5(1):26-34. https://doi.org/10.17352/2455-815x.000038

50. Kumar B, Dhar S, Paul S, Paramesh V, Dass A, Upadhyay PK, et al. Microbial biomass carbon, activity of soil enzymes, nutrient availability, root growth and total biomass production in wheat cultivars under variable irrigation and nutrient management. Agronomy. 2021;11(4):669. https://doi.org/10.3390/agronomy11040669

51. Prasanna R, Nain L, Pandey AK, Saxena AK. Microbial diversity and multidimensional interactions in the rice ecosystem. Archives of Agronomy and Soil Science. 2011;58(7):723-44. https://doi.org/10.1080/03650340.2010.537325

52. Muthusamy Y, Sengodan K, Arthanari M, Kandhasamy R, Gobianand K. Biofertilizer and consortium development: An updated review. Current Agriculture Research Journal. 2023;11(1):1-17. https://doi.org/10.12944/carj.11.1.01

53. Peng Y, Fei L, Jie F, Hao K, Liu L, Shen F, et al. Effects of Bio-organic fertilizer on soil infiltration, water distribution and leaching loss under muddy water irrigation conditions. Agronomy. 2023;13(8):2014. https://doi.org/10.3390/agronomy13082014

54. Button M, Nivala J, Weber KP, Aubron T, Müller R. Microbial community metabolic function in subsurface flow constructed wetlands of different designs. Ecological Engineering. 2014;80:162-71. https://doi.org/10.1016/j.ecoleng.2014.09.073

55. Mikha MM, Vigil MF, Benjamin JG. Long-term tillage impacts on soil aggregation and carbon dynamics under wheat-fallow in the central great plains. Soil Science Society of America Journal. 2013;77(2):594-605. https://doi.org/10.2136/sssaj2012.0125

56. Kwiatkowski CA, Harasim E, Feledyn-Szewczyk B, Antonkiewicz J. Enzymatic activity of loess soil in organic and conventional farming systems. Agriculture. 2020;10(4):135. https://doi.org/10.3390/agriculture10040135

57. Gómez-Silván C, Arévalo JC, Pérez J, González-López J, Rodelas B. Linking hydrolytic activities to variables influencing a submerged membrane bioreactor (MBR) treating urban wastewater under real operating conditions. Water Research. 2012;47(1):66-78. https://doi.org/10.1016/j.watres.2012.09.032

58. Kim D. Physico-Chemical Conversion of Lignocellulose: Inhibitor effects and detoxification strategies: A Mini Review. Molecules. 2018;23(2):309. https://doi.org/10.3390/molecules23020309

59. Ludewig U. Improving the efficiency and effectiveness of global phosphorus use: focus on root and rhizosphere levels in the agronomic system. Frontiers of Agricultural Science and Engineering. 2019;6(4):357-65. https://doi.org/10.15302/j-fase-2019275

60. Elyamine AM, Moussa MG, Ismael MA, Wei J, Zhao Y, Wu Y, et al. Earthworms, rice straw and plant interactions change the organic connections in soil and promote the decontamination of cadmium in soil. International Journal of Environmental Research and Public Health. 2018;15(11):2398. https://doi.org/10.3390/ijerph15112398

61. Bertrand M, Barot S, Blouin M, Whalen JK, Oliveira T de, Roger-Estrade J. Earthworm services for cropping systems. a review. Agronomy for Sustainable Development. 2015;35:553-67. https://doi.org/10.1007/s13593-014-0269-7

62. Choosai C, Jouquet P, Hanboonsong Y, Hartmann C. Effects of earthworms on soil properties and rice production in the rainfed paddy fields of Northeast Thailand. Applied Soil Ecology. 2010;45(3):298-303. https://doi.org/10.1016/j.apsoil.2010.05.006

63. Gough EC, Owen K, Zwart RS, Thompson J. A Systematic review of the effects of arbuscular mycorrhizal fungi on root-lesion nematodes, Pratylenchus *spp*. Frontiers in Plant Science. 2020;11:923. https://doi.org/10.3389/fpls.2020.00923

64. Mukkram Ali Tahir R, Noor-us-Sabah, Afzal M, Sarwar G, Rasool Noorka I. Smart Nutrition Management of Rice Crop under Climate Change Environment [Internet]. Protecting Rice Grains in the Post-Genomic Era. IntechOpen; 2019. https://doi.org/10.5772/intechopen.86094

65. Sinha D, Tandon PK. An overview of nitrogen, phosphorus and potassium: Key players of nutrition process in plants. Sustainable solutions for elemental deficiency and excess in crop plants. 2020:85-117. https://doi.org/10.1007/978-981-15-8636-1_5

66. Sainju UM, Ghimire R, Pradhan GP. Nitrogen Fertilization II: Management practices to sustain crop production and soil and environmental quality [Internet]. Nitrogen Fixation. IntechOpen; 2020. Available from: https://doi.org/10.5772/intechopen.86646

67. Qi D, Wu Q, Zhu J. Nitrogen and phosphorus losses from paddy fields and the yield of rice with different water and nitrogen management practices. Scientific Reports 2020;10(1):9734. https://doi.org/10.1038/s41598-020-66757-5.

68. Muhammad Aslam M, Akhtar K, Karanja JK, Noor-ul-Ain, Ullah Haider F. Understanding the adaptive mechanisms of plant in low phosphorous soil [Internet]. Plant Stress Physiology. IntechOpen; 2021. Available from: https://doi.org/10.5772/intechopen.91873

69. Karamanos RE, Flore NA, Harapiak JT. The impact of phosphorus fertilizer placement on crop production. Agricultural Research & Technology. 2017;11(4):555817. https://doi.org/10.19080/artoaj.2017.11.555817

70. Oo AZ, Tsujimoto Y, Rakotoarisoa NM, Kawamura K, Nishigaki T. P-dipping of rice seedlings increases applied P use efficiency in high P-fixing soils. Scientific Reports. 2020;10(1):11919. https://doi.org/10.1038/s41598-020-68977-1

71. Chen X, Gao Y, Hong L, Tang H. Effects of phosphorus supply on root morphology and phosphorus uptake in maize seedlings under different water regimes. American Journal of Agriculture and Forestry. 2020;8(1):22-9. https://doi.org/10.11648/j.ajaf.20200801.14

72. Bargaz A, Lyamlouli K, Chtouki M, Zeroual Y, Dhiba D. Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. Frontiers in Microbiology. 2018;9:1606. https://doi.org/10.3389/fmicb.2018.01606

73. Kumar R, Mahajan N, Naresh RK, Dhaliwal SS, Kumar A, Chandra MS, et al. Agro-technological options for scaling up crop productivity, soil health and water footprint in rice based cropping system in sub-humid (purvanchal) region of Uttar Pradesh, India: A Review. International Journal of Current Microbiology and Applied Sciences. 2019;8(7):2679-700. https://doi.org/10.20546/ijcmas.2019.807.330

74. Johannisson J, Hiete M. A structured approach for the mitigation of natural methane emissions-lessons learned from

anthropogenic emissions. Journal of Carbon Research.2020;6 (2):24. https://doi.org/10.3390/c6020024

75. Walling E, Vaneeckhaute C. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. Journal of Environmental Management. 2020;276:111211. https://doi.org/10.1016/j.jenvman.2020.111211

76. Narayanamoorthy A, Jothi P. Water saving and productivity benefits of SRI: A study of tank, canal and groundwater irrigated settings in South India. Water Policy. 2018;21(1):162-77. https://doi.org/10.2166/wp.2018.199

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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