



REVIEW ARTICLE

Enhancing nitrogen dynamics, soil health and yield intensification in rice-based cropping systems through rice straw incorporation

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Abstract

Use of a combine harvester for rice is responsible for leaving huge amounts of rice straw in harvested fields. As mechanisation in agriculture becomes widely adopted across the country, this leaves behind a good amount of straw. Farmers often burn this valuable organic resource, which increases greenhouse gas concentrations in the atmosphere. However, if this straw material is incorporated into the soil, it can significantly improve soil health, particularly its nutrient status. The beneficial effects of this practice are reflected in the higher yields of crops. Accordingly, this review focuses on nitrogen dynamics, crop performance, including yield and soil health status under rice ecosystems. Nitrogen (N) dynamics in soil-plant systems involve physical, chemical and biological processes. Physically, straw incorporation enhances soil structure, water retention and aggregation, providing a conducive environment for nutrient cycling. Chemically, it influences N immobilisation and mineralisation processes, balancing the availability of nitrogen for crops. Biologically, straw incorporation promotes microbial activity and diversity, particularly nitrogen-fixing and nitrifying bacteria, which play a crucial role in N availability to crops. These processes collectively improve soil nitrogen pools, enhance nitrogen use efficiency and reduce nitrogen losses through leaching or gaseous emissions. This results in synchronisation of nitrogen supply with crop demand, which will increase productivity and reduce pollution from the rice ecosystem.

Keywords: crop residue incorporation; carbon sequestration; greenhouse gas emission; N mineralization; rice yield

Introduction

Rice is a staple food crop for more than half of the global population and its demand is projected to rise significantly by 2050 (1-3). As rice production intensifies to meet this growing demand, managing the vast quantities of rice straw produced becomes a critical challenge, especially in intensively cultivated systems like rice-rice and rice-wheat. In India alone, approximately 10 million hectares of land under rice-wheat systems are located in the Indo-Gangetic Plains (IGPs), contributing heavily to national food security (4). However, these systems are increasingly facing sustainability issues, including declining soil fertility, falling groundwater tables and the widespread environmental hazard of rice straw burning (5 - 8). Straw is the only organic material available in significant quantities to most rice farmers. About 40 % of nitrogen (N), 30-35 % of phosphorus (P), 80 - 85 % of potassium (K) and 40 - 50 % of sulfur (S) absorbed by the crop remains in vegetative residues at maturity (9). These nutrients can be recycled if straw is returned to the field, offering an opportunity to enhance soil fertility and reduce synthetic fertiliser requirements. The potential agronomic and environmental benefits of rice straw incorporation (RSTI) are summarised in Fig. 1. However, the practical difficulties associated with straw collection and

economic limitations often lead to open-field residue burning, which not only results in significant nutrient losses but also contributes to severe greenhouse gas (GHG) emissions and air pollution (10-12). The incorporation of rice straw into soil is gaining attention as a sustainable alternative, particularly when combined with optimised fertiliser-N management. While incorporation initially causes nitrogen immobilisation due to the high C: N ratio (~80:1) and biochemical recalcitrance of straw (12-16 % silica and 6-7 % lignin), this is typically followed by mineralisation that can enhance soil N supply (13, 14). Consequently, higher rates of fertiliser-N may be required in the short term to overcome immobilisation, but long-term residue return improves soil organic matter content, enzymatic activity and nitrogen use efficiency (NUE) (15 - 17). Although most research has focused on rice-wheat systems, rice-rice cropping sequences prevalent in eastern and southern India also generate substantial quantities of straw and face similar sustainability challenges. Yet, there is a dearth of systematic synthesis on how straw incorporation affects N dynamics, soil health and yield intensification in such systems. Notably, the combined application of fertiliser-N with rice straw can influence microbial activity, enzymatic processes and the mineral N pool, impacting both short-term productivity and long-term soil health (18 - 20).

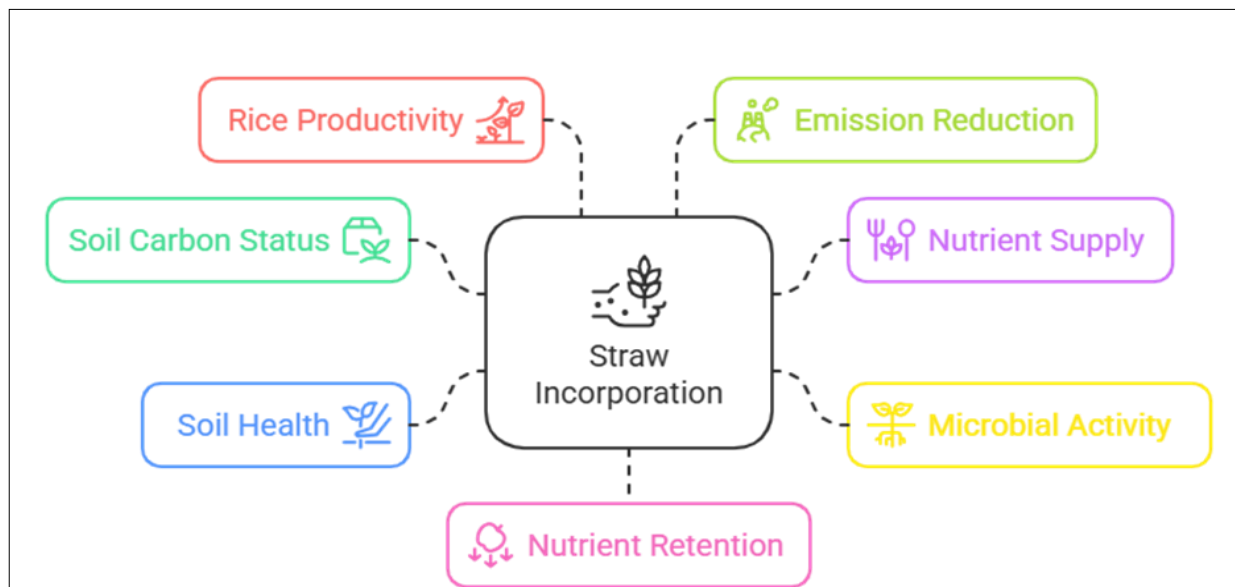


Fig. 1. Benefits of straw incorporation.

This review, therefore, aims to consolidate and critically evaluate the current understanding of rice straw incorporation with respect to N cycling and yield responses in rice-based cropping systems. Since the early eighties of the last century, researchers have discussed mainly the impact of straw management on soil fertility status and crop productivity. However, in this review, efforts have been made to discuss various aspects of nitrogen dynamics, soil health and yield sustainability as a resultant effect of rice straw management in rice-based cropping systems. By integrating insights across soil biochemical, microbial and environmental dimensions, it provides a comprehensive and up-to-date perspective while pinpointing unresolved knowledge gaps, thereby offering a stronger scientific basis for guiding future research and management practices.

Mechanisms of nitrogen transformation with straw incorporation

Overview of the nitrogen cycle in paddy fields

The nitrogen cycle in paddy fields is a microbially driven set of transformations that operate under unique redox conditions imposed by alternating wetting and drying (21). While the general nitrogen forms and processes mirror those in upland soils, the predominance of anaerobic conditions in flooded rice systems fundamentally alters the pathways and efficiency of nitrogen transformation. In aerobic upland soils, nitrate (NO_3^-) is the dominant form of inorganic nitrogen due to active nitrification. In contrast, in flooded paddy soils, ammonium (NH_4^+) becomes the principal and more stable form due to suppressed nitrification, as limited oxygen restricts the activity of nitrifying microorganisms (22). A thin oxidised zone persists around the soil-water interface and rice rhizosphere, allowing limited nitrification to occur in these microsites. Urea is the most widely used N fertiliser in rice cultivation and is rapidly hydrolysed to NH_4^+ after application (23). This NH_4^+ can either be directly absorbed by rice plants or undergo limited oxidation to NO_3^- in the rhizosphere. The NO_3^- produced can then diffuse into surrounding anaerobic zones and participate in several anaerobic processes, including denitrification, where N is sequentially reduced to nitrite, nitric oxide, nitrous oxide (N_2O) and dinitrogen gas (N_2) (24). Another important pathway is anaerobic ammonium oxidation (anammox), where NH_4^+ and nitrite are converted directly into N_2 gas, while DNRA transforms NO_3^- into NH_4^+ , aiding nitrogen retention in reduced environments (25).

Nitrification itself is mediated by AOB such as *Nitrosomonas* and NOB like *Nitrobacter*. The rate-limiting step in this process is the oxidation of NH_4^+ to hydroxylamine by ammonia monooxygenase (AMO), followed by its conversion to nitrite by hydroxylamine oxidoreductase and finally to nitrate via nitrite oxidoreductase (26). Although these transformations are essential for nitrogen turnover, they also contribute to N_2O emissions, a potent greenhouse gas with a global warming potential far exceeding that of CO_2 . Microbial community composition plays a central role in governing nitrogen cycling in rice fields. Soil microorganisms, including bacteria, archaea and fungi, drive nitrification, denitrification and mineralisation processes. Studies have shown that high-yielding rice systems tend to harbour a greater abundance of microbial taxa involved in N transformation and enhanced expression of nitrate transporters in plant roots (27). Nitrogen mineralisation, the microbial conversion of organic N into ammonium, is a key step in making nitrogen available to plants. It begins with the breakdown of complex organic compounds into simpler molecules such as amino acids, which are then further mineralised into NH_4^+ . A portion of this inorganic nitrogen may become temporarily immobilised in microbial biomass or organic matter, acting as a buffer against N losses and helping maintain a steady nitrogen supply during crop growth (28).

Despite these internal cycling processes, paddy fields are prone to nitrogen losses through several pathways. Surface-applied urea is susceptible to ammonia volatilisation, while simultaneous nitrification-denitrification in oxic-anoxic interfaces can lead to gaseous losses. During periods of drainage, NO_3^- may leach out of the soil profile. Incomplete denitrification under fluctuating redox conditions also contributes to N_2O emissions. On the other hand, biological nitrogen fixation (BNF) by free-living or associative diazotrophs in floodwater and rhizosphere can contribute additional nitrogen, although typically insufficient to meet full crop demand (29, 30).

Role of straw in nitrogen immobilisation and mineralisation

Following straw incorporation, nitrogen initially becomes immobilised as soil microorganisms decompose the carbon-rich residues. Due to the high C:N ratio of rice straw, microbes sequester available inorganic nitrogen (mainly NH_4^+ and NO_3^-) into their biomass to meet their nutritional needs. As decomposition

progresses and microbial demand for nitrogen is met, biomass senescence and turnover initiate net nitrogen mineralisation. This phase is characterised by the enzymatic breakdown of microbial cells and organic residues, releasing NH_4^+ through ammonification. Key enzymes such as proteinases, peptidases, nucleases and chitinases facilitate the degradation of complex N-containing compounds into amino acids and other soluble intermediates, which are subsequently catabolized to release plant-available ammonium (31).

The rate and extent of this transition from immobilisation to mineralisation are governed by several factors. Substrate quality, particularly the C: N ratio, lignin and silica content of straw, plays a dominant role, as high-lignin residues persist longer and release nitrogen more slowly (32, 33). Microbial community composition also influences the timing and efficiency of nitrogen turnover; fungal-dominated systems tend to prolong immobilisation, whereas bacteria-dominated communities accelerate N cycling. Additionally, environmental conditions such as soil temperature, moisture, aeration and redox potential modulate the decomposition environment and microbial activity. Spatial heterogeneity in microbial colonisation around straw particles adds further complexity (34). Thus, while straw incorporation may temporarily suppress N availability, particularly in the early stages, it ultimately contributes to the long-term enrichment of mineralizable organic nitrogen, enhanced microbial biomass turnover, improved soil fertility and increased nitrogen use efficiency (Fig. 2).

Role of straw in ammonification and nitrification

In rice-based systems, straw incorporation significantly influences the processes of ammonification and nitrification by modifying substrate availability and microbial dynamics. Ammonification, the biological conversion of organic nitrogen into NH_4^+ , is primarily driven by microbial degradation of complex organic molecules such as proteins, nucleic acids and amino sugars present in rice straw (35). When straw is incorporated into soil, microbial activity accelerates due to the availability of carbon substrates, triggering the synthesis of extracellular enzymes like proteases, nucleases and chitinases. These enzymes catalyse the breakdown of organic matter, releasing

amino acids and other low-molecular-weight nitrogenous compounds that are subsequently mineralised to NH_4^+ . However, due to the high C : N ratio and lignocellulosic nature of straw, a portion of the available N may be immobilised temporarily within the microbial biomass, delaying the net release of NH_4^+ (36).

Once NH_4^+ is formed, it serves as the substrate for nitrification, an oxidative two-step microbial process that converts NH_4^+ to nitrite (NO_2^-) and then to nitrate (NO_3^-). This transformation is facilitated by two key groups of chemoautotrophic microbes: ammonia-oxidising bacteria (AOB) such as *Nitrosomonas* spp., which oxidise NH_4^+ to NO_2^- via hydroxylamine (NH_2OH) using the enzyme AMO; and nitrite-oxidising bacteria (NOB), like *Nitrobacter* spp., which subsequently oxidise NO_2^- to NO_3^- via nitrite oxidoreductase (NXR) (37). Notably, recent evidence also highlights the role of ammonia-oxidising archaea (AOA) in these transformations, particularly under low-nutrient conditions. The presence of straw can indirectly regulate nitrification by altering the NH_4^+ pool and the redox microenvironments within soil aggregates. Furthermore, straw-induced increases in microbial biomass can lead to temporary immobilisation of NH_4^+ , reducing its availability for nitrifiers. Over time, as microbial turnover occurs and redox gradients re-establish post-submergence, nitrification resumes, contributing to the NO_3^- pool. Hence, the role of straw is multifaceted; it first governs ammonification through microbial substrate supply and then modulates nitrification through spatial, biochemical and ecological constraints on nitrifier activity. Moreover, low molecular weight organics produced by microbial decomposition inhibit the proliferation of chemoautotrophic nitrifiers, compounding the suppression of nitrification during early decomposition stages (38).

Interaction with soil microbes (e.g., *Nitrosomonas* and *Azotobacter*)

Straw incorporation significantly affects soil microbial communities by providing a physical substrate and abundant organic carbon, which stimulates the growth and activity of heterotrophic microbes. This influx of carbon-rich material indirectly influences functional microbial groups involved in nitrogen cycling, including AOB such as *Nitrosomonas*, which are chemoautotrophs that rely on inorganic substrates like NH_4^+ for energy. During the early stages of straw

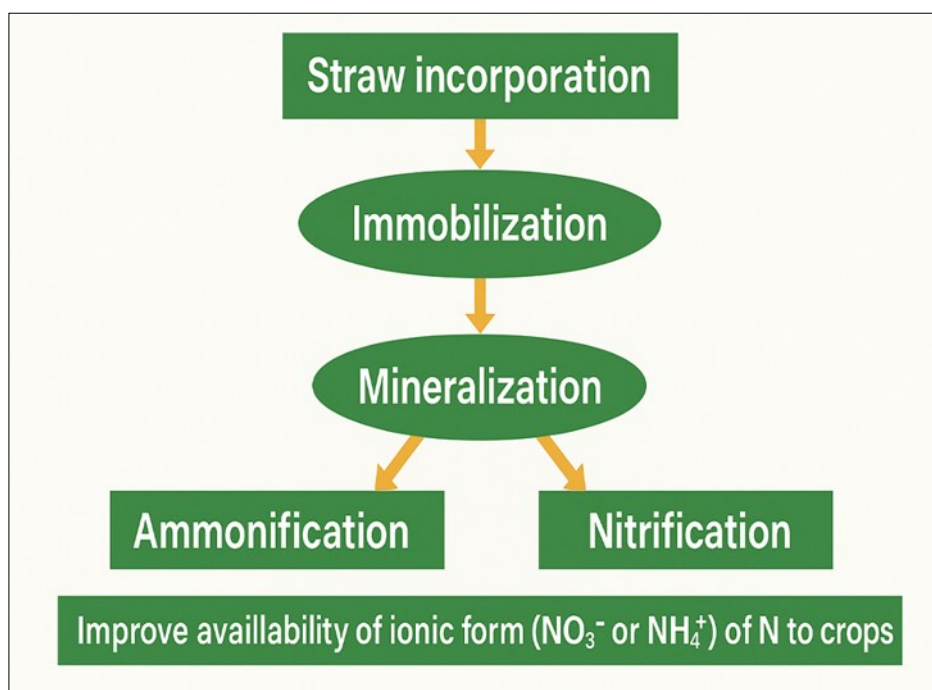


Fig. 2. Fate of straw incorporation on the soil N cycle.

decomposition, the enhanced activity of heterotrophic microbes leads to intense competition for NH_4^+ and reduces oxygen availability in microsites, thereby suppressing AOB activity. Moreover, low-molecular-weight organic compounds released during microbial decomposition have been shown to inhibit the proliferation of nitrifiers, further delaying the nitrification process. As microbial demand subsides and oxygen conditions improve, particularly in oxic zones such as the rhizosphere or soil surface, AOB activity gradually resumes, facilitating the oxidation of NH_4^+ to nitrite (NO_2^-) and sustaining the nitrification pathway (39).

Simultaneously, straw incorporation supports the activity of free-living nitrogen-fixing bacteria such as *Azotobacter*, which utilise organic carbon from decomposing residues as an energy source to fix atmospheric nitrogen (N_2) into bioavailable forms like NH_4^+ under aerobic conditions. Moreover, associative nitrogen-fixing bacteria like *Azospirillum* primarily respond to root exudates rather than external organic amendments (40). The increase in root biomass and exudation under straw-amended soils creates a favourable rhizosphere environment for these diazotrophs. These microbial shifts not only enhance soil biological nitrogen inputs but also improve synchronisation between N release and its uptake by the crop. As a result, straw incorporation strengthens the functional interactions between nitrogen fixers and nitrifiers, ultimately contributing to higher nitrogen availability, better fertiliser-use efficiency and improved crop performance in the field (30).

Enzymatic activities and microbial dynamics

Straw incorporation into soil significantly stimulates enzymatic activities and microbial dynamics, which are fundamental to organic matter decomposition and nitrogen transformation. Microorganisms secrete a variety of extracellular enzymes, such as proteases, ureases, cellulases and chitinases that catalyse the breakdown of complex organic compounds in straw into simpler, assimilable forms (41). Proteases and ureases, in particular, are crucial for the mineralisation of organic nitrogen, converting proteins and urea into NH_4^+ , thus supporting plant nitrogen uptake. The presence of straw enhances substrate availability, thereby increasing microbial demand and activity, which in turn amplifies enzyme production. This leads to accelerated decomposition of the residue and release of nutrients, especially during the later stages of microbial succession when the immobilised N becomes available through microbial turnover (42).

In parallel, straw inputs significantly modify soil microbial dynamics by enhancing microbial biomass, diversity and community composition. The addition of labile carbon sources creates a favourable environment for copiotrophic organisms, including both bacterial and fungal communities, with shifts often observed towards higher abundances of beneficial groups such as ammonia oxidizers, diazotrophs and decomposers (43). Several studies have reported increased microbial diversity, often measured using indices such as the Shannon Index (Equation 1), following straw incorporation. For example, significant increases in Shannon diversity were observed alongside rises in microbial biomass nitrogen (MBN) and MBC, indicating a more functionally resilient microbial community (44).

$$H' = -\sum(\pi_i \times \ln \pi_i) \quad (\text{Eqn 1})$$

Where,

H' = Shannon diversity index, π_i = proportion of individuals belonging to the i th species ($\pi_i = n_i / N$), n_i = number of individuals of species i , N = total number of individuals across all species

These changes promote higher microbial respiration, nitrogen mineralisation rates and biological nitrogen fixation (45). These changes lead to increased soil microbial respiration, improved nitrogen mineralisation rates and enhanced biological nitrogen fixation. Furthermore, the straw-induced rise in MBN and MBC serves as a transient sink for nutrients, buffering against N losses and supporting long-term nutrient recycling (44). Overall, the synergistic enhancement of enzymatic activities and microbial interactions under straw incorporation forms a critical mechanism driving nitrogen cycling and improving soil fertility in rice-based systems.

Research evidence on the impact of RSTI in rice-based systems

Nitrogen dynamics and availability

RSTI influences N availability in paddy soils through a complex balance of immobilisation and mineralisation processes. NH_4^+ concentrations peaked at day 14 with chemical fertiliser and around day 20 with 20 t ha^{-1} of straw compost, indicating slower mineralisation due to microbial N demand (46). Nitrate (NO_3^-) levels were also highest on day 30 for low compost rates (2.5 – 5 t ha^{-1}) and on day 40 for higher straw applications (10 – 20 t ha^{-1}), but remained much lower than NH_4^+ due to suppressed nitrification under flooded conditions. This early reduction in nitrate concentration, often referred to as nitrate depression, is a typical consequence of the combined effects of microbial immobilisation and low redox potential in submerged conditions, where NO_3^- is both suppressed in formation and prone to denitrification losses. Research indicates that available N in soils treated with straw (C: N = 61) remained consistently lower than in controls due to enhanced net immobilisation. Notably, ~48 % of applied fertiliser N was immobilised within 10 days, with immobilisation reaching 49 % under flooded-straw conditions, compared to just 8 % under non-flooded-no straw (NF-NS) conditions after 160 days (47). In a study, only 13 – 14 % of N from ^{15}N -labelled rice straw was recovered in crops during the growing season and 23–24 % of straw N was mineralised (48). Although the short-term contribution to soil inorganic N was low, long-term incorporation of rice straw at 5 mg $\text{ha}^{-1} \text{year}^{-1}$ over 12 years significantly improved soil fertility and increased total N and crop uptake. However, these benefits often emerge only after several cropping cycles, meaning that farmers may experience initial yield or N availability penalties if straw is not managed with sufficient supplemental N. The microbial mechanism underlying these processes was highlighted that straw return modified soil bacterial communities involved in N cycling (49). For example, proteobacteria (including Beta- and Gammaproteobacteria), nitrospirae and chloroflexi increased in abundance at critical rice growth stages (tillering to heading), facilitating synchronised N release and uptake. Relative SIN (soil inorganic nitrogen) values in straw treatments were significantly lower in early stages but improved as microbial activity increased over time. Yet, the timing and extent of these microbial responses vary widely with soil texture, climate and water management, which may explain why not all studies report consistent improvements in N availability. Research indicates that 7.5 t ha^{-1} of straw incorporation led to a 19.9 % increase in N mineralisation and a 30.5 % increase in N uptake, while reducing N leaching by 6.6 % and NH_3 loss by 54.5 %.

Recovery efficiency (RE) and agronomic efficiency (AE) rose by 39.1 % and 29.8 %, respectively (50). Recent studies highlight the potential of coated nitrogen fertilisers in enhancing nitrogen use efficiency (NUE) and synchronising N release with crop demand. Research indicates that a novel lignosulfonate-coated controlled-release urea significantly improved N content (by 1.3 - fold), leaf greenness, photosynthetic efficiency and grain yield (by ~35 %) in rice compared to conventional urea, even at reduced N doses (51). Similarly, research indicates that a one-time application of polymer-coated urea (PCU) enhanced root morphological traits (deep root proportion, root length density) and physiological activity (zeatin content, root oxidative activity), leading to a 10 % yield increase and a 46.2 % improvement in agronomic NUE over local farmer practices (52). These benefits were attributed to the gradual and sustained release of N over 100 days, aligning nutrient availability with critical growth stages. Likewise, controlled-release urea (CRU) combined with straw resulted in N use efficiency (NUE) values ranging from 46.7 % to 71.6 % (mean: 56.1 %), which were 58.3 - 149.4 % higher than conventional fertiliser (CF) and 42.0-150.5 % greater than CF plus straw (CF+WS) (53). These improvements were attributed to better alignment of N release with plant demand and enhanced microbial-mediated N transformation. Still, the magnitude of NUE gains reported across studies suggests context dependence; differences in coated fertiliser type, soil environment and crop management all influence outcomes, highlighting the need for site-specific recommendations rather than one-size-fits-all approaches. Together, these studies highlight that while rice straw initially immobilises N, its progressive mineralisation, especially when integrated with efficient fertiliser strategies, can substantially improve nitrogen dynamics and availability in paddy systems (Table 1).

Soil organic carbon and soil fertility

RSTI plays a vital role in enhancing soil organic carbon (SOC) and overall soil fertility across diverse rice-based systems. Research demonstrated that SOC accumulation was highest in flooded paddy (FP) soils at 1.00 mg ha⁻¹ yr⁻¹, compared to 0.68 mg ha⁻¹ yr⁻¹ in upland (UL) and 0.24 mg ha⁻¹ yr⁻¹ in paddy-upland (PU) systems, with the highest carbon conversion ratio (9.11 %) recorded in FP (54). Using a 35-year DNDC model simulation, research found that SOC stabilised in 13 years under rice straw (RS) incorporation and 43 years under rice straw compost (RSC) (55). This led to a 9.2 % increase in grain yield with RS and 11.2 % with RSC, while discontinuing residue return caused a sharp SOC decline and yield losses, confirming the long-term necessity of organic inputs. Research highlighted that rape straw (RS) incorporation, especially when combined with integrated basal fertiliser (IBF) and alternate wetting and drying (AWD) irrigation, significantly improved SOC, microbial biomass

carbon (MBC) and soil nutrient cycling. In contrast, wheat straw increased dissolved organic carbon (DOC), which also supported microbial activity (53). Under non-flooded plastic film mulching conditions, SOC increases of 6.4 %, 7.6 % and 12.2 % over three consecutive years (2008-2010) with straw incorporation, along with 20.4-23.9 % increases in plant N uptake and consistent gains in alkali-hydrolyzable N, Olsen P and exchangeable K under higher N inputs (135-180 kg N ha⁻¹) (57). Research indicates that long-term rice residue incorporation, particularly when combined with green gram inclusion and optimised nitrogen management, led to improvements in soil organic carbon and available NPK content (58). Although rice straw decomposition typically produces organic acids that can lower soil pH, their study reported a slight increase in pH, likely due to the buffering effects of nitrogen amendments and legume-induced alkalinity under integrated nutrient management practices. This highlights that the chemical outcomes of straw incorporation may vary depending on management conditions. Further research confirmed that long-term straw incorporation in a rice-wheat system raised SOC by 10.7 %, total N by 6.1 %, available N by 22.0 %, available P by 8.6 % and available K by 40.1 %, while reducing soil bulk density by 16.3 %, thus enhancing root growth and nutrient uptake (59). Nonetheless, challenges such as slow decomposition of high-lignin straw, potential short-term nutrient lock-up and shifts in soil acidity need to be carefully managed to fully realise the fertility benefits. Together, these findings strongly support RSTI as an effective long-term strategy to improve soil fertility, boost nutrient availability and build SOC reserves, making it essential for sustainable rice-based production systems (Table 2).

Soil biological properties and enzyme activities

RSTI significantly enhances soil biological properties and enzyme activities, contributing to improved soil fertility and nutrient cycling in rice-based systems. Research indicates that long-term straw incorporation in a rice-rice-oilseed rape system increased MBC by 22.5-39.7 % and MBN by 18.3-34.2 %, along with marked increases in enzyme activities related to C, N and P acquisition rising by 33.6 %, 42.2 % and 14.1 %, respectively. These gains were further supported by higher DOC and ammonium levels, with conventional tillage outperforming no-till in promoting enzymatic activity (60). Research showed that NPK + straw (NPK+ s) enhanced polyphenol oxidase activity by 12.8 %, while NPK + manure (NPK + m) significantly boosted β -glucosidase (24.8 %), acid phosphatase (24 %), urease (9.2 %) and sucrase (23.2 %), improving organic matter decomposition and nutrient turnover (61). Research indicates that incorporating 7.5 Mg ha⁻¹ of straw with 120-150 kg N ha⁻¹ increased urease activity by 28.6-34.7 % and L-asparaginase by 8.6 %, along with a twofold rise in glomalin-related soil protein (GRSP), enhancing

Table 1. Summary of studies on nitrogen dynamics and availability with rice straw incorporation

Main focus	Key findings	Citations
N mineralisation, ammonium & nitrate forms	Rice straw compost delayed N release; higher ammonium at 20 t ha ⁻¹ ; nitrate was suppressed under flooded conditions	(46)
Redox effect on N availability	Straw induced strong immobilisation; under flooding, N availability declined after 30 days.	(47)
N mineralisation and uptake (short vs long)	23-24 % of straw N mineralised; long-term application improved N uptake and inorganic N content	(48)
Bacterial influence on N transformation	Straw affected microbial community; enhanced N synchrony at panicle stage with Proteobacteria & Nitrospirae.	(49)
Simulated N flow in straw-amended soil	30.5 % higher N uptake, 19.9 % more N mineralisation and reduced N losses with 7.5 t ha ⁻¹ straw	(50)
NUE with fertiliser and straw combination	CRU+WS increased NUE by 89 % over CF; CF+WS marginally better than CF alone	(53)

Table 2. Summary of studies on SOC and soil fertility with rice straw incorporation

Main focus	Key findings	Citations
SOC accumulation in various cropping systems	SOC increased most in flooded paddies ($1.00 \text{ mg ha}^{-1} \text{ yr}^{-1}$); 9.11 % C conversion efficiency	(54)
Straw + water-nutrient management effects	Rape straw + AWD + IBF improved SOC, DOC and microbial C, boosting yield and fertility.	(56)
Straw + N input on SOC and fertility (PFMC)	SOC increased by up to 12.2 %; plant N uptake improved by ~24 %; better N, P and K availability	(57)
Straw + high fertilisation in rice–wheat system	SOC increased by 10.7 %, total N by 6.1 %, available K by 40.1 % and bulk density reduced by 16.3 %	(59)

soil structure and N availability (62). Similarly, research also indicates that ditch-buried straw return (DB-SR) elevated microbial activity, with fluorescein diacetate hydrolase rising by 107.2–124.1 %, soil respiration by up to 107.8 % and microbial metabolic diversity index (H') by 34.8–125.3 % (63).

Enzyme responses included sharp increases in β -glucosidase (89.2–141.2 %), acid phosphatase (up to 47.9 %) and arylsulphatase (52.9–97.4 %), although urease activity declined after rice cultivation but rebounded in wheat soils. Dual straw returning (15.3 t ha^{-1} , including 9.1 t ha^{-1} rice straw and 6.2 t ha^{-1} wheat straw) enhanced MBC by 91.6 % (from 286.90 to 549.81 mg kg^{-1}), MBN by over 60 % and DOC by nearly 95 % compared to the control. Microbial quotient (Qmb) rose from 2.03 % to 2.70–2.88 % (49). Bacterial diversity (Shannon index) and abundance of functional phyla like Proteobacteria, Nitrospirae and Chloroflexi also increased during the rice growth cycle, with Nitrospirae rising ~60 % at heading and Chloroflexi 2–3 x higher in DR treatments. These microbial shifts synchronised nitrogen cycling with crop demand and were positively linked to total N uptake and yield through structural equation modelling. Conservation agriculture practices, especially combining no till (NT) or reduced tillage with straw return, favour soil microbial habitat restoration, boosting microbial biomass and enzyme activity crucial for nitrogen transformations.

Research indicates that 18 years of no-till and residue return in a Chinese anthrosol increased topsoil (0–10cm) total nitrogen by up to 34 % compared to conventional tillage, while enhancing urease, catalase and invertase activities (64). A global meta-analysis covering 14,308 observations confirmed that no-till with straw mulch raised enzyme activities by 13–23 %, with the strongest increases in nitrogen-cycling enzymes like urease under no-till plus straw return (65). In southern China's double-rice fields, residue return with rotary or no-tillage significantly elevated microbial biomass carbon and nitrogen in both 0–10cm and 10–20cm layers (66). While these findings consistently highlight the benefits of straw incorporation in enhancing microbial and enzymatic activity, responses can vary with soil type, climate and management practices. For instance, excessive stimulation of enzymes like urease or acid phosphatase may

accelerate nutrient losses or acidify soils under certain conditions, while shifts in microbial dominance could disrupt ecological balance. Thus, although straw incorporation generally promotes soil fertility, its outcomes are not universally positive and careful integration with site-specific nutrient and water management is required to avoid potential trade-offs (Table 3).

Soil physical properties

Incorporation of rice straw has shown marked improvements in soil physical properties, including moisture retention, bulk density, structural stability and crack resistance across various soil textures and management regimes. In a pot study with silty clay loam soil, application of rice straw at 7 % to the total weight of the soil increased soil moisture status (at saturation) from 35 % (without straw) to 44.7 %. These also reduce soil bulk density from 1.38 to 1.03 g/cm^3 (67). Deep tillage with Straw return (DTS) significantly reduced subsoil bulk density by up to 12.5 % in the 14–28 cm layer, compared to shallow tillage with straw mulch (STS), promoting deeper root growth (68). DTS also redistributed nutrients to lower soil layers, enhancing nitrogen and phosphorus availability by 15–35 % and extending grain-filling duration by 1.5 days through better root support and soil structure. Alternate wetting and moderate drying (AWMD) combined with straw return could reduced bulk density, promoted honeycomb-like pore structures (observed via SEM) and enhanced both macro- and micro-aggregate stability (69). The R-AWMD treatment led to better infiltration, root aeration and microbial activity due to improved porosity and redox conditions. Research highlighted that long-term rice residue incorporation (RRI), especially when combined with green gram inclusion (GGI), increased SOC by up to 45.7 % and available nitrogen by 20.3 %, improving structural stability and buffering capacity (58). Potassium availability also rose by 69.4 %, indicating a robust enhancement in soil fertility and aggregate formation, though direct measurements of physical traits were inferred from associated chemical improvements. However, it is important to note that the extent of these improvements can vary depending on soil type and climatic conditions. For instance, coarse-textured soils may show smaller reductions in bulk density compared to fine-textured soils, while in

Table 3. Summary of studies on soil biological properties and enzyme activities with rice straw incorporation

Main focus	Key findings	Citations
Straw return + tillage on microbial activity	MBC increased by 22.5–39.7 %; enzyme activities (C, N, P-acquisition) significantly enhanced	(60)
Long-term fertilisation regimes on soil biology	NPK + manure increased urease (9.2 %), acid phosphatase (24 %) and β -glucosidase (24.8 %)	(61)
Straw + N effects on enzymes and glomalin	Urease rose by 28.6–34.7 %; L-asparaginase by 8.6 %; glomalin 2x higher in straw + N treatments	(62)
Ditch-buried straw return on soil enzymes	FDA activity increased by 107–124 %; β -glucosidase activity increased by 89–141 %; GRSP increased by up to 190.7 %, while urease response showed variable trends.	(63)
Straw return and microbial community structure	MBC increased by 91.6 %, MBN increased by 60 % and both the Shannon diversity index and key nitrogen-transforming phyla were enhanced.	(49)

sub-humid regions with fluctuating rainfall patterns, residue decomposition and its contribution to aggregation may differ from those in continuously flooded systems. Such variability highlights the need for location-specific assessments before generalising the physical benefits of straw incorporation (Table 4).

Growth, biomass and yield attributes

RSTI consistently demonstrated positive effects on plant growth parameters, biomass accumulation and grain yield across diverse agroecosystems, although responses varied with management practices and environmental conditions. Dual straw return (DR) in a rice-wheat rotation significantly enhanced leaf area index (LAI), leaf area duration (LAD), crop growth rate (CGR) and total biomass from panicle initiation onward, despite a temporary suppression during early vegetative stages (49). The DR treatment led to an 11.5 % increase in CGR and over 49.9 % improvement in nitrogen uptake, culminating in a grain yield increase of 12.6 % (12.24 t ha⁻¹) over the control in 2019. Research indicates that composted straw at 20 t ha⁻¹ promoted plant height (71.8 cm) and tillering (16 tillers/plant), though chemical fertilisers outperformed compost for grain yield (18.59 g pot⁻¹ vs. 11.14 g at 10 t ha⁻¹ compost) (46). The 100 % straw incorporation with green manure significantly increased tiller and panicle number (up to 599 m² and 7506 kg ha⁻¹ grain yield in DS 2000), especially from the third season onward (70). Spikelets per panicle also rose by 8-10 % over control, though 1000 grain weight remained unchanged. Water management combined with straw handling also influenced performance. AWD irrigation improved

panicle number (by 23 %), spikelets per panicle (12 %) and shoot biomass (42 %) over continuous flooding (CF) (71). However, straw management alone had limited yield effects. The integrating rice straw with microbial decomposers and 75 % RDF achieved the highest yields (6101 kg ha⁻¹), marking a 43.1 % gain over RDF alone, supported by robust tillering and LAI improvements (72). This performance was largely attributed to the action of lignocellulolytic microbial consortia, which enhanced straw decomposition by producing cellulases and lignin-degrading enzymes, thereby accelerating nutrient mineralisation and improving nitrogen availability during critical growth stages. Early researchers reported that nutrient uptake dynamics 15 t ha⁻¹ straw improved phosphorus availability to 95 mg/kg and grain yield up to 8.01 t ha⁻¹ under alternate submergence-drying (ASD) (73). Similarly, the 14.6 % increase in early rice yield (5.5 mg ha⁻¹) in flooded paddies with NPK + straw, though responses in upland or rotation systems were less consistent (54). Beyond mean yield, straw incorporation improved yield stability, reducing yield variability (CV by 25.8 %) and increasing the sustainable yield index (SYI by 8.2 %), especially under low-light conditions (59). In wheat, a 22.9 % increase in grain yield with 7.5 t ha⁻¹ straw, achieving 6503.8 kg ha⁻¹ under optimal N and water use, while also enhancing SOC by 25 % and improving N uptake by 30.5 % (Table 5) (50).

Nitrogen use efficiency (NUE) and fertiliser recovery

RSTI has emerged as a promising strategy to enhance NUE and fertiliser nitrogen recovery in rice-based systems, though outcomes

Table 4. Summary of studies on soil physical properties with rice straw incorporation

Main focus	Key findings	Citations
Straw effects on bulk density, moisture and cracking	Bulk density decreased by 25 %, moisture content increased by 28 % and cracking was delayed by 50 % at higher straw application rates.	(67)
Tillage + straw effects on soil layers	Deep tillage + straw reduced deep-layer BD by 12.5 % and improved nutrient distribution.	(68)
Straw + AWM irrigation on structure and aeration	AWMD combined with straw reduced bulk density, increased porosity and formed honeycomb-like aggregates; redox potential (Eh) and soil structure were also improved.	(69)
Residue and green gram on SOC and structure	Soil organic carbon increased by 45.7 %; available potassium increased by 69.4 %; improvements in soil aggregation and porosity were inferred.	(58)

Table 5. Summary of studies on growth, biomass and yield attributes with rice straw incorporation

Main focus	Key findings	Citations
Straw effects on growth, biomass and yield	DR increased LAI, CGR and N uptake by 49.9 % and yield by 12.6 % over the control.	(49)
Compost effects on rice growth and yield	20 t ha ⁻¹ compost improved plant height and yield, but lower than chemical fertiliser	(46)
Straw + green manure on yield traits	Tillers increased by 30 %; spikelets per panicle increased by 8-10 %; grain yield increased by 25.4 % in T ₃ (straw + green manure).	(70)
AWD + straw on biomass and yield	Alternate wetting and drying increased grain yield by 15 %; rice straw incorporation improved root and shoot biomass by 42 to 73 %, depending on the season.	(71)
Straw + decomposer + 75 % RDF on growth	Plant height reached 106.2 cm; the number of tillers was 25 per hill; grain yield increased by 43.1 % compared to the treatment with the recommended dose of fertiliser alone.	(72)
Straw and water regime on yield, NPK	Grain yield reached 8.01 t ha ⁻¹ under alternate submergence-drying (ASD) with 15 t ha ⁻¹ straw incorporation; nitrogen uptake was 79 % higher than the control.	(73)
Straw on yield stability	Grain yield reached 8.01 t ha ⁻¹ under ASD with 15 t ha ⁻¹ rice straw incorporation, accompanied by a 79 % increase in nitrogen uptake compared to the control.	(59)
Straw + fertiliser in various systems	In the flooded paddy (FP) system, early rice yield increased by 14.6 %, while upland (UL) crops also showed positive yield responses to the combined application of straw and nitrogen and phosphorus fertilisers.	(54)
RSTI effects on wheat yield and soil	Wheat yield increased by 22.9 % under rice straw incorporation at 7.5 t ha ⁻¹ combined with 120 kg N ha ⁻¹ , along with improvements in nitrogen use efficiency and soil quality.	(50)

vary with management practices, soil conditions and straw application rates. In long-term field and simulation studies, early works demonstrated that incorporating 7.5 t ha⁻¹ of rice straw increased nitrogen uptake by 30.5 %, nitrogen mineralisation by 19.9 % and significantly reduced N losses via leaching (-6.6 %) and ammonia volatilisation (-54.5 %) (50). This led to a 29.8 % increase in agronomic efficiency (AE) and a 39.1 % rise in recovery efficiency (RE) compared to no-straw control. However, higher nitrogen inputs (150 kg N ha⁻¹) increased uptake but also amplified losses, ultimately reducing NUE. Similarly, controlled-release urea (CRU) combined with wheat straw (CRU+WS) enhanced NUE by 89.0 % over conventional fertiliser (CF), with efficiency values ranging from 46.7 % to 71.6 %, due to synchronised nitrogen release and improved microbial activity (53). In contrast, CF+WS improved NUE by only 4.6 %, showing a limited effect without controlled N release. Long-term straw returning also improved NUE by enhancing soil biological and chemical properties. Over 49.9 % higher nitrogen uptake during the critical panicle initiation stage under combined rice and wheat straw incorporation (DR) compared to control, attributed to higher SOC, microbial biomass and favourable shifts in bacterial communities involved in N cycling (49). While short-term fertiliser N recovery from straw was low (~13-14 %), long-term application significantly increased inorganic N content and gross mineralisation rates (up to 84 % higher under +RS), boosting N supply from soil organic pools rather than fertiliser alone (48). Likewise, research demonstrated improved nitrogen uptake with straw application under both continuous submergence (CS) and ASD, with up to 79 % increase in N uptake under CS and higher soil-derived N contributions under ASD (73). However, potential challenges remain, as excessive nitrogen fertilisation combined with straw return can accelerate nutrient imbalances, increase the risk of element accumulation in soil and reduce efficiency gains over the long term, especially in coarse-textured or poorly buffered soils. Collectively, these studies emphasise that while rice straw incorporation can initially lead to nitrogen immobilisation, strategic integration with optimised N rates, irrigation scheduling (e.g., AWD) and enhanced-release fertilisers can substantially improve NUE and reduce fertiliser dependency and environmental losses in rice-based cropping systems (Table 6).

Greenhouse gas emissions and environmental footprint

Rice straw incorporation into paddy systems significantly influences greenhouse gas (GHG) emissions, especially methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂), with the magnitude of emissions largely dependent on the interaction between straw type, quantity, nitrogen input and water management. Across most

studies, straw incorporation markedly increased CH₄ emissions due to the provision of labile carbon substrates that stimulate methanogenic activity in anaerobic soil environments. For instance, reported that combining straw with NPK fertilizers resulted in CH₄ emissions of 1675 kg ha⁻¹ yr⁻¹ over 120 % higher than NPK alone (74). Similarly, CH₄ emissions increased by 118.6 % in single rice and 79.0 % in rice-wheat systems with straw addition. While methane was the dominant contributor to total GHG emissions in flooded systems, straw's impact on N₂O varied (75). Under cooler or early-season conditions, a 43 % reduction in N₂O due to microbial nitrogen immobilization were found (76). Conversely, in warmer seasons or under intermittent irrigation like AWD, N₂O emissions increased. For example, research indicates showed that N₂O emissions were 153 – 399 % higher in controlled-release urea with straw (CRU+WS) compared to conventional fertilization (53). Interestingly, research indicates that although AWD raised N₂O emissions by 63.4 %, concurrent straw return reduced them by up to 59.1 %, likely by promoting complete denitrification (69). The effect of straw on CO₂ emissions was also substantial. High straw rates, especially under low nitrogen input, led to significant increases in CO₂ emissions due to elevated microbial respiration (77). However, when paired with moderate straw and nitrogen input, emissions per unit yield were minimised, suggesting a better carbon use efficiency. Mitigation strategies emerged prominently in several studies. AWMD consistently lowered CH₄ emissions. Furthermore, integrating rape straw instead of wheat straw enhanced methane oxidation and reduced emissions due to a higher *pmoA/mcrA* gene ratio. Despite increased emissions, straw incorporation often improved yield, which helped reduce yield-scaled emissions when paired with proper nitrogen management. Similarly, the net GHG emissions dropped by 28.0 % under AWMD with straw return, due to improved carbon sequestration and reduced CH₄ output (69). However, the long-term sustainability of straw incorporation remains context-dependent. While it improves soil fertility and reduces residue burning, persistent increases in CH₄ emissions under flooded conditions may offset these benefits unless combined with mitigation practices. Thus, balancing yield gains with net reductions in GHG is essential to ensure true environmental sustainability of this practice (Table 7).

Conclusion

A balanced fertilisation strategy, whether purely synthetic or combined with organic amendments, can sustain high yields in double-cropping rice systems, but residue management critically shapes both productivity and GHG outcomes. The burning of rice

Table 6. Summary of studies on nitrogen use efficiency (NUE) and fertiliser recovery with rice straw incorporation

Main focus	Key findings	Citations
Rice straw incorporation effects on NUE and N losses	Agronomic efficiency increased by 29.8 %, recovery efficiency by 39.1 %, while ammonia loss decreased by 54.5 % and nitrate leaching by 6.6 % under rice straw incorporation at 7.5 t ha ⁻¹ .	(50)
Fertiliser type and straw on NUE	Controlled-release urea with straw incorporation increased nitrogen use efficiency by 89 % compared to conventional fertiliser, while conventional fertiliser with straw increased it by only 4.6 %; the improvement under controlled-release urea was due to better synchronisation of nitrogen release with plant demand.	(53)
Straw return effects on N uptake	Nitrogen uptake increased by 49.9 % under the dual straw returning (DR) treatment; this was associated with enhanced microbial biomass and higher soil inorganic nitrogen content.	(49)
Short- and long-term N recovery	Short-term nitrogen recovery was 13-14 % from rice straw and 4-5 % from compost; in the long term, rice straw incorporation increased soil nitrogen content and mineralisation rates.	(48)
Straw + water regime on NPK uptake	Nitrogen uptake increased by 79 % under continuous submergence (CS) with 15 t ha ⁻¹ straw incorporation; nitrogen derived from fertiliser (Ndff) rose to 70 % and phosphorus and potassium uptake also improved.	(73)

Table 7. Summary of studies on greenhouse gas emissions and environmental footprint with rice straw incorporation

Main focus	Key findings	Citations
Straw + NPK effects on GHG and CF	Methane emissions increased by 120 % with straw application; total greenhouse gas emissions reached 47300 kg CO ₂ -equivalent ha ⁻¹ yr ⁻¹ compared to 24100 kg CO ₂ -equivalent under NPK alone; the carbon footprint rose to 3.9 kg CO ₂ -equivalent per kg of grain.	(74)
Seasonal straw impact on GHGs	In the early season, global warming potential (GWP) decreased with straw application; however, in the late season, methane emissions increased fourfold, raising GWP to 21367 kg CO ₂ -equivalent per hectare.	(76)
GHGs across cropping systems	Methane emissions increased by 72-118 % with straw incorporation; GWP was highest in the double rice (DR) system at 20663 kg CO ₂ -equivalent per hectare. However, combining straw with nitrogen application reduced yield-scaled greenhouse gas emissions.	(75)
Straw + AWD irrigation on GHGs	Straw incorporation increased methane emissions by 92.6 %, while AWD reduced methane emissions by 27 %, GWP by 25.3 % and greenhouse gas intensity (GHGI) by 28.3 % compared to conventional irrigation with straw (R-CI).	(69)
Fertiliser + straw effects on GHGs	Compared to conventional fertiliser (CF), CF with wheat straw (CF+WS) increased methane emissions by 215.3 % and controlled-release urea with straw (CRU+WS) increased nitrous oxide emissions by up to 399.3 %. GHGI rose by 171 % to 181 % under straw-amended treatments.	(53)
Straw type, N rate & AWD on CH ₄	Wheat straw incorporation increased methane emissions by 44-57 %, while rape straw led to an increase of 23-36 %. AWD reduced methane emissions by 24 % and the combination of rape straw with AWD lowered yield-scaled methane emissions by 16 %.	(56)
Straw & N rate effects on emission eff.	High straw combined with low nitrogen increased both carbon dioxide and nitrous oxide emissions, whereas moderate straw with low nitrogen reduced nitrous oxide emissions per unit yield and improved emission efficiency.	(77)

straw in situ removes the essential nutrients and microbes (as well as producing large levels of GHG emissions) and the direct incorporation of fresh straw at transplanting can also marginally increase yield, but over doubles CH₄ emissions and increases the carbon footprint of the crop. To capture the benefit of straw towards soil fertility without driving up emissions, rice straw should be applied 2-3 weeks before the fallow period rather than at transplanting, allowing partial aerobic decomposition that reduces methanogenic substrate in the subsequent flooded season. To achieve sustainable rice production, widespread adoption of straw incorporation is essential. Integrating this practice with optimised nitrogen management can balance productivity with environmental conservation, paving the way for climate-smart agriculture. Farmers, researchers and policymakers must work collaboratively to promote and implement these sustainable practices for long-term agricultural resilience.

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Authors' contributions

TS contributed to conceptualization, supervision and overall guidance of the study. SS contributed to conceptualization, literature search and selection, data synthesis and thematic organization, writing-review and editing and overall manuscript refinement. MDR contributed to conceptualization and supervision. SM contributed to literature search and selection, data synthesis and thematic organization and writing-original draft preparation. NS contributed to writing-review and editing. All authors reviewed and approved the final version of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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