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REVIEW

Microbial aggregates and functional materials for mitigating soil nitrogen loss: a review

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Abstract Nitrogen (N) plays a critical role in crop growth, development, and yield. In global agriculture, however, about 40 to 60 percent of nitrogen applied to soil is lost through nitrous oxide (N_2O) emissions, nitrate (NO_3^-) leaching, and ammonia (NH_3) volatilization, resulting in significantly reduced crop yields and environmental issues, such as water body eutrophication, soil degradation, and increased greenhouse gas emissions. While a range of mitigation strategies have been explored, effective and scalable solutions that simultaneously enhance N retention in soil and promote crop uptake remain limited. In this context, integrated approaches that combine microbial aggregates with functional materials represent a promising yet underexplored pathway. This review examines the structural functions of microbial aggregates and the properties of common functional materials, emphasizing their mechanisms of action in reducing soil nitrogen loss and their potential contributions to mitigating environmental pollution. Additionally, the physical, chemical, and biological interactions during the synergistic application of these technologies were investigated, resulting in a 14–26% increase in soil nitrogen retention and a 15–35% increase in crop yields through improved inter-root nitrogen supply. This review aims to provide practical strategies for reducing agricultural nitrogen loss and its associated environmental hazards while promoting sustainable agricultural practices.

Keywords Microbial aggregates · Functional material · Nitrogen loss · Biochar · Nanomaterial · Soil ecosystem

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1 Introduction

Nitrogen (N) plays a critical role in crop growth, development, and yield, significantly promoting photosynthesis, protein synthesis, and biomass accumulation (Zayed et al. 2023). Appropriate application of nitrogen fertilizer can increase crop yields by

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47–56%; however, the over-application could deplete soil fertility and inhibit plant growth, therefore resulting in losing a great amount of soil nitrogen (Foley et al. 2011). A significant amount of applied nitrogen is lost through NH_3 volatilization (Louis et al. 2016). NH_3 emitted into the atmosphere neutralizes acidic compounds to form ammonium salts, which contribute to widespread soil acidification upon deposition, exacerbate global climate change, pose multiple threats to ecosystems, and significantly reduce biodiversity (Duan et al. 2016; Khan et al. 2012). Nitrogen leaching from agricultural land poses a significant threat to water security; nitrate leaching losses reach up to 63.3 kg N ha^{-1} yr^{-1}. Among China's 532 rivers, 82% suffer nitrate nitrogen pollution at varying levels (Wang and Li 2019). Nitrate contamination in drinking water has affected 150 million people globally, significantly increasing the risk of infant methemoglobinemia ("blue baby syndrome") and colorectal cancer (Grout et al. 2023; Ward et al. 2018). Overall, soil nitrogen loss has become a major concern for global agricultural and environmental sectors, with widespread impacts on ecosystem sustainability and public health.

In recent years, several studies have reported the N cycle and related N loss in various agricultural ecosystems (e.g., wheat, maize, rice, vegetable) (Cui et al. 2014; Wang et al. 2018b, 2019a). Globally, on average 15% and 22% of fertilizer N applied in maize and wheat systems, respectively, are lost as nitrate through leaching, respectively (Zhou and Butterbach-Bahl 2014), while 0.81% and 1.21% of N in maize and sugarcane systems, respectively, are lost in the form of N_2O (Yang et al. 2021; Zhang et al. 2019). Approximately, 12.8% of applied N in cereal and 14.5% in vegetable systems are lost as the NH_3 (Ma et al. 2021). Table 1 quantifies the global average nitrogen inputs into cropping systems and the direct nitrogen outputs via various loss pathways (Zhao et al. 2022). Global nitrogen use efficiency stands at merely 0.42, with applied nitrogen fertilizers lost through runoff, leaching and volatilization, whilst a significant portion of the remainder enters the soil organic nitrogen pool (Cui et al. 2018). This organic nitrogen is then subject to sequential microbial degradation, progressing through soluble organic forms before final mineralization into plant-available ammonium (NH_4^+–N) and nitrate (NO_3^-–N) (Cui et al. 2018; Zhang et al. 2015). Soluble inorganic nitrogen is particularly prone to loss through surface runoff and water seepage, with nitrates accounting for 6.7–19% of dissolved nitrogen losses (Wang and Li 2019; Zhan et al. 2024). Natural factors such as soil moisture content and precipitation, as well as the application of chemical fertilizers, increase soil nitrogen loss (Xin et al. 2019). NH_3 volatilization, particularly after urea or animal manure application, is a significant source of gaseous nitrogen loss, adversely affecting crop yields and increasing production costs (Li et al. 2022). Developing effective methods to mitigate soil nitrogen loss has become a significant area of investigation in contemporary studies.

Microbial aggregates are complex communities of diverse microorganisms and their secretions that develop on submerged substrates (Wu et al. 2012), comprising various biological components that form intricate food webs; they can enhance nitrogen cycling and utilization, significantly increasing nitrogen-use efficiency compared to single-strain inoculants (Rooney et al. 2020; Zulkifly et al. 2013). The rapid advancement of functional materials in the past decade has created substantial opportunities for effectively managing agricultural nitrogen loss, reducing NH_3 volatilization and nitrate leaching in field trials by 13.1–29.5% and 24.5–34.9%, respectively (Elrys et al. 2023). Numerous studies have investigated the

Table 1 Global mean N input and direct N output through different N loss pathways in cropping systems

Variable	n	Average N rate (kg N ha^{-1} yr^{-1})	N output (kg N ha^{-1} yr^{-1})		Background output (kg N ha^{-1} yr^{-1})		
			mean	95%CI	n	mean	95%CI
N_2O emission	158	296	5.50	4.27–7.05	57	3.75	1.98–5.94
NH_3 volatilization	73	179	12.1	9.12–15.8	18	6.98	3.27–11.7
Nitrate leaching	56	208	52.1	37.4–68.9	14	16.3	5.34–36.0
N runoff	91	385	11.3	7.43–15.7	12	14.6	7.69–25.8
Net fruit N removal	121	369	81.3	63.5–99.7	23	36.9	21.3–56.2

The mean N rate and N output refer to the measured data of N treatment except for no N treatment. *CI* confidence interval, *n* mean number of observations effects of functional materials on plant nitrogen utilization and reducing nitrogen loss in agricultural systems (Ding et al. 2024; Jia et al. 2025; Wang et al. 2024a). These materials can significantly enhance the physicochemical properties of soil, with biochar increasing organic matter content by up to 18.5% and improving water retention, polymer-coated fertilizers reducing nutrient leaching by 35.7% with, and nanomaterials boosting crop yields by 22.1% through better nutrient uptake (Qian et al. 2023; Shan et al. 2024). These enhancements promote the growth of beneficial microorganisms and increase the efficiency of soil nitrogen conversion (Wang et al. 2020b).

Comparative analyses of reviews in this field from the last 5 years indicate that the application of microbial aggregates and functional materials holds significant potential for reducing soil nitrogen loss (Table 2). However, their effectiveness when used individually is limited, and the complex interactions occurring when they are combined within the soil nitrogen cycle have not been fully investigated, preventing their widespread application and adoption in agricultural practices. This review systematically explores the synergistic mechanisms of microbial aggregates and functional materials in mitigating soil nitrogen loss, bridging this critical research gap. This review is unique in that it not only examines the effects of individual factors on soil nitrogen retention but also delves into the intricate interactions between functional materials and microbial aggregates. Additionally, more effective and friendly environment soil management strategies integrating recent advancements in material science with microbial ecology theories are proposed.

2 Role of microbial aggregates in mitigating soil nitrogen loss

Microbial aggregates are intricate structures ranging in size from micrometers to millimeters that are formed in natural environments by a diverse array of microbial cells (Liao et al. 2022). These cells adhere to, entangle with, or surround one another, attaching via substances including extracellular secretions, organic polymers, and mineral particles (Grout et al. 2023). Typically developing in moist substrates, they have a diverse composition including bacteria, fungi, algae, protozoa, and metazoans. These aggregates can increase localized microbial densities by 10–100 fold, and form complete food webs that facilitate complex interactions between different species (Boulêtreau et al. 2011). Over a seven-year maize field trial under warm temperate climate (15.3 °C; 1197 mm annual precipitation) and Ferralic Cambisols soil, the formation of diverse microbial aggregates fostered enhanced nitrogen fixation efficiency, concurrently mitigating nitrogen loss and providing a stable nitrogen source for crops (Li et al. 2019).

2.1 Abiotic matrix

Extracellular polymeric substances (EPS) consisting of extracellular secretions, organic polymers, and mineral particles are a significant component of microbial aggregates. These substances facilitate microbial aggregation by binding cells through various interactions, including hydrophobic, electrostatic, hydrogen bonding, ionic, and van der Waals forces (Fig. 1) (Ding et al. 2015; Sheng et al. 2010). Extracellular secretions released by algae, bacteria, and other microorganisms during growth and metabolism largely consist of proteins, polysaccharides, humic acids, nucleic acids, and lipids (Fulaz et al. 2019). Proteins include enzymes that are directly involved in nitrogen conversion; Nag et al. (2024) found that nitrogen-fixing enzymes convert atmospheric nitrogen into NH_3, increasing available soil nitrogen. Similarly, polysaccharides improve the aggregation and biofilm formation of nitrogen-fixing microorganisms by sequestering targeted soil cations, thereby enhancing their viability and persistence in the rhizosphere (Wang et al. 2017). Humic acids promote microbial activity and nitrogen conversion by increasing soil nitrogen bioavailability (Ampong et al. 2022). Nucleic acids play a crucial role in regulating microbial gene expression (Wang et al. 2024a), while lipids enhance microbial adaptation in soil by modulating membrane fluidity, both of which promote nitrogen conversion (Erimban and Daschakraborty 2022). In cotton fields with alkaline calcareous soil under semi–arid climate, EPS facilitate the formation of diverse microbial aggregates, which enhance plant nutrient availability and soil fertility, ultimately promoting superior crop growth and yield (Ahmad et al. 2021).

Organic polymers are a nutrient source for microorganisms, playing an essential role in the conservation

Table 2 Typical cases utilizing functional materials and microorganisms to improve nitrogen fixation

Research focus	Innovation	Year	References
Enhanced nitrogen fixation and cadmium passivation in inter-root soils using biochar-loaded nitrogen-fixing bacteria	Combining biochar with nitrogen-fixing bacteria enhances soil nitrogen fixation efficiency and effectively passivates cadmium	2025	Chang et al. (2025)
Nanotechnology in agriculture, with particular focus on the nitrogen cycle	New ideas for optimizing the nitrogen cycle using nanotechnology are presented	2023	Wang et al. (2023)
Microplastic interference with natural nitrogen cycling	Multiple pathways of interaction between microplastics and the nitrogen cycle are summarized	2021	Shen et al. (2022)
Tracking microbial-mediated nitrogen transformations using natural abundance isotope studies and microbiological approaches	Integrating isotope analysis of natural abundance in the nitrogen cycle with traditional microbiological techniques	2024	Deb et al. (2024)
Biochar addition effects on soil properties, nitrogen cycling enhancement, and pollutant reduction	Summarized the multifunctional effects of biochar in different soil types and environmental conditions	2024	Aziz et al. (2024)
Modification strategies for bismuth-based photocatalysts to improve nitrogen fixation efficiency	Various modification strategies for bismuth-based photocatalysts are summarized, emphasizing their potential to enhance photocatalytic activity	2025	Yin et al. (2025)
Nitrogen transformation mechanisms driven by functional microorganisms during high-temperature fermentation in exogenous fermentation systems	Specific microbial mechanisms of action on nitrogen transformation during high-temperature fermentation conditions are detailed	2022	Zhou et al. (2022)
Soil nitrogen fixation by synergistic microbial aggregates with functional materials	Optimizing interactions between functional materials and specific microbial communities to improve soil nitrogen fixation efficiency	2025	This work

Cases of functional material and microorganism application for nitrogen fixation within the last 5 years, their scope of application, and positive effects. The results of comparative studies demonstrate the advantages of synergistic nitrogen fixation by functional materials and microbial aggregates

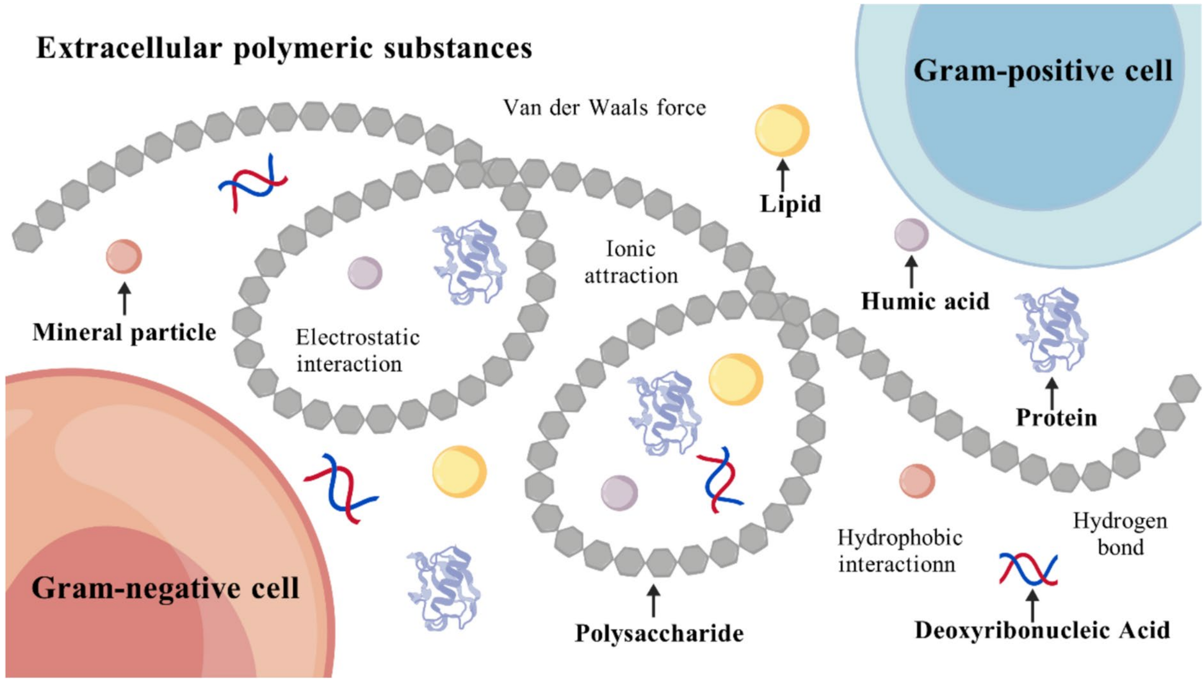

Fig. 1 Extracellular polymeric substances are composed of various components situated between cells, including polysaccharides, proteins, deoxyribonucleic acid, mineral particles, and phospholipids. These components have diverse interactions, including electrostatic interactions, Van der Waals forces, ionic attractions, hydrophobic interactions, and hydrogen bonds, which play a vital role in maintaining microbial aggregate stability

of organic matter while reducing nitrogen loss and leaching (Zhou et al. 2017). Mineral particles provide physical support for EPS, increasing microbial viability and function in the soil nitrogen cycle by creating a stable microenvironment (Zhao et al. 2021b). EPS include both bound (B-EPS) and soluble EPS (S-EPS); B-EPS includes sheaths, capsule polymers, gels, loosely bound polymers, and attached organic materials, while S-EPS comprises soluble macromolecules, colloids, and mucus (Teng et al. 2020). S-EPS primarily includes soluble microbial products such as α-D-glucopyranose and β-D-glucopyranose, whereas the principal component of B-EPS is protein (Janissen et al. 2015; You et al. 2017). Overall, EPS plays a crucial role in enhancing microbial aggregation, promoting nutrient cycling, and improving soil health.

2.2 Biotic composition

Microbial aggregates consist of bacteria, fungi, algae, protozoa, and epifauna, all of which play significant and often complementary roles in the soil nitrogen cycle (Sheng et al. 2010). Nitrogen-fixing bacteria, such as *Rhizobium leguminosarum* and *Bradyrhizobium japonicum*, convert atmospheric nitrogen into bioavailable nitrogen through symbiotic relationships with leguminous plants, providing essential nutrients for plants and other organisms (Dinnage et al. 2019). Free–living nitrogen-fixing bacteria, including *Azotobacter vinelandii* and *Azospirillum brasilense*, also contribute to nitrogen fixation, enriching soil nitrogen pools (Venado et al. 2025). During the 12–week experiment, when *Rhizophagus irregularis*, *Septoglomus deserticola*, and *Gigaspora gigantea* were inoculated into the soil, these fungi significantly accelerated organic matter decomposition by enhancing nitrogen mineralisation, thereby increasing the concentration of plant-available nitrogen (Kohler et al. 2017). In a field trial on alkaline meadow soil with a 143–day frost-free period and extreme temperatures ranging from − 39.2 to 39.8 °C, the application of Trichoderma conidial suspensions (0.7 or 1.4 g in 200 mL water) at the 15 and 25–day post-emergence stages of maize improved soil properties (e.g., organic matter and total nitrogen) during the 129–day growth cycle and increased crop yield by 4.87–12.41% (Fu et al. 2019). Algae, such as the cyanobacteria *Nostoc* and *Anabaena*, synthesize organic compounds through photosynthesis, providing energy to microorganisms while facilitating nitrogen cycling through both fixation and photosynthetic activity (Lu et al. 2024).

Microfauna adds another layer of regulation to this complex system. Protozoa, including ciliates such as *Tetrahymena thermophila* and amoebae such as *Acanthamoeba castellanii*, significantly influence nitrogen mineralization by preying on bacteria and other microorganisms; this regulates the microbial community structure and can enhance nitrogen utilisation efficiency (Chen et al. 2007). Metazoans, including multicellular animals such as rotifers, nematodes, insects, and their larvae, are important mediators in the soil ecosystem that facilitate nutrient recirculation and release through their feeding and decomposition activities, influencing the overall nutrient balance of the soil (Briones 2018; Ji et al. 2022). Microbial community diversity enhances soil nitrogen cycling efficiency through interactions and functional complementarities, supporting ecosystem health and stability (Alimohammadi et al. 2020).

2.3 Soil nitrogen loss regulation by microbial aggregates

Biological nitrogen fixation is a pivotal component of the natural nitrogen cycle (Cheng 2008). Compared to microorganisms existing in dispersed forms, those forming aggregates can more efficiently carry out the nitrogen fixation process and convert it into biomass (Ibrahim et al. 2020). Autotrophic bacteria, including cyanobacteria, serve as key primary producers and diazotrophs in soil aggregates, contributing to nitrogen input through biological nitrogen fixation. However, their activity and ecological function in terrestrial environments are constrained by soil–specific limitations such as low water availability, restricted light penetration, and intense competition for nutrients (Sciuto and Moro 2015). Field trials conducted in red soil paddy fields under humid subtropical monsoon climate conditions (annual mean temperature 17.6 °C, annual precipitation of 1788.8 mm, and a frost–free period of 258 days, application rate: 300 kg ha^{-1} (dry basis), cyanobacteria capable of nitrogen fixation from atmospheric nitrogen and environmental inorganic nitrogen play a significant role in maintaining rice yields while simultaneously reducing the application of synthetic nitrogen fertilizers (Song et al. 2022).

Nitrogen assimilation is the process by which inorganic nitrogen is converted into organic forms retained in biomass through microbial aggregates (Liu et al. 2016a). The reduced form of ammonium can be directly assimilated by microalgae, while the oxidized forms of nitrogen (nitrate and nitrite) must first be reduced to ammonium before being incorporated into amino acids through glutamate and adenosine triphosphate (ATP) (Gonçalves et al. 2017). In photosynthetic microorganisms such as cyanobacteria, ATP is primarily obtained through photophosphorylation. Conversely, within heterotrophic microbial communities, ATP derives from the respiratory decomposition of organic matter (Liu et al. 2021a). Klawonn et al. (2015) found significantly higher (2–threefold) rates of nitrogen fixation in highly diverse microbial aggregates, suggesting complex interactions between various nitrogen–fixing bacteria and photosynthetic microorganisms that promote more efficient nitrogen transformation. Microbial aggregates with high community diversity that are photosynthetically active play a crucial role in nitrogen cycle regulation (Fig. 2).

Microbial aggregates help mitigate soil nitrogen loss by promoting organic matter decomposition and mineralization, facilitating nitrogen cycling, and converting organic nitrogen into plant–absorbable inorganic nitrogen (Heijboer et al. 2016; Sun et al. 2020a). Additionally, the organic substances in microbial aggregates, such as extracellular polysaccharides and polymers, enhance soil physical properties by improving its aggregation and water retention capacity. This enhancement enhances microbial survival and nitrogen fixation, and is essential for regulating soil nitrogen loss (Büks and Kaupenjohann 2016; Cheng et al. 2020). Overall, microbial aggregates significantly enhance soil nitrogen cycling and reserves through biological nitrogen fixation, inorganic nitrogen assimilation, and the improvement of soil physical properties. Their activity and diversity are essential for effective soil nitrogen management, enhancing nitrogen use efficiency and promoting agricultural sustainability.

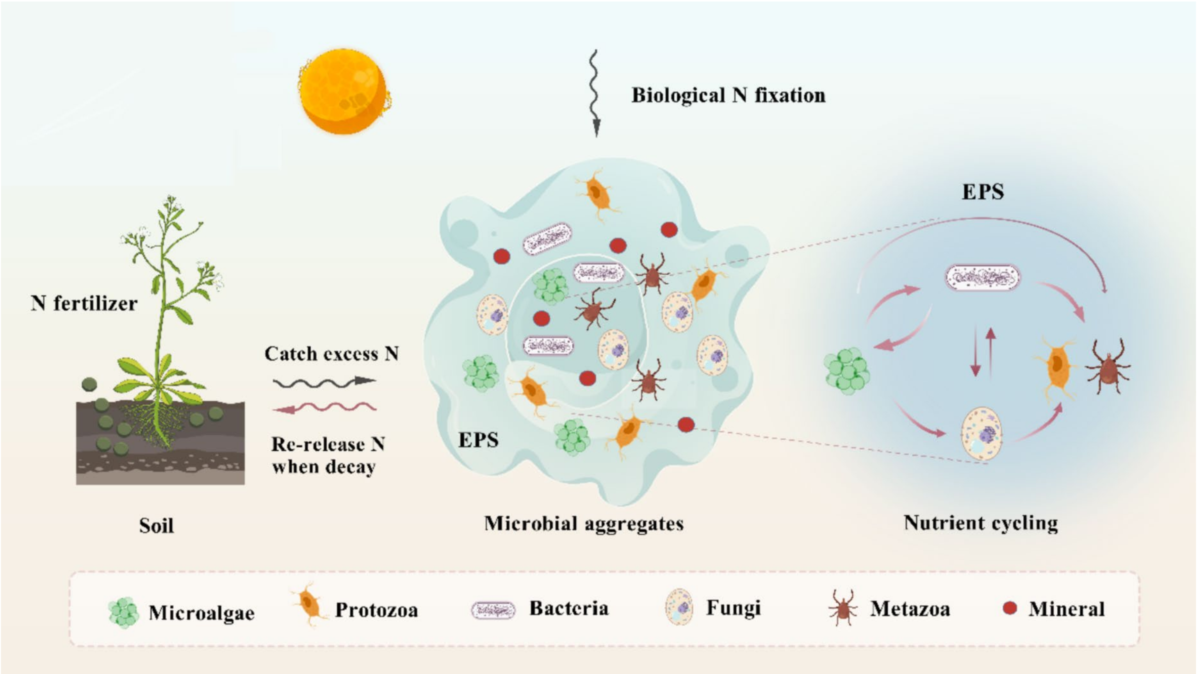

Fig. 2 Microbial aggregates play an important role in the nitrogen cycle, converting atmospheric nitrogen into a plant-available form. The right inset shows microbial aggregates composed of bacteria, fungi, protozoa, metazoans, extracellular polymeric substances, and minerals. These aggregates enhance microbial interactions by facilitating nutrient cycling. Bacteria convert nitrogen into ammonia and nitrate, making it available for plant uptake. Fungi release nitrogen by breaking down organic matter and forming reciprocal relationships with plants. Protozoa and metazoans consume bacteria and fungi to control their populations and facilitate nutrient cycling. Overall, these functions ensure the health and stability of the soil ecosystem

2.4 Metabolic pathways of microbial aggregates in the soil nitrogen cycle

The role of microbial aggregates in reducing soil nitrogen loss is also closely linked to their functional genes, proteins, and enzyme activities, which are crucial for nitrogen fixation, transformation, and cycling (Han et al. 2021). Nitrogen cycling in soil can be subdivided into three main processes: decomposition, assimilation, and dissimilation (Fig. 3) (Song et al. 2025). Decomposition entails the release of high molecular weight soil organic nitrogen (SON) during the breakdown of plant litter, which can be further degraded into low molecular weight dissolved organic nitrogen (DON) (Yu et al. 2024). Assimilation is the uptake and utilization of DON, ammonium, or nitrate by plants and microorganisms for growth and reproduction (Ardichvili et al. 2024). Dissimilation encompasses the oxidation and reduction of nitrogen, such as nitrification and denitrification (Jassal et al. 2010).

Nitrogen–fixing microorganisms such as *Rhizobium* and *Azotobacter* convert atmospheric nitrogen into NH_3 using the nitrogenase complex encoded by the *nif* gene cluster (Zuluaga et al. 2024). During nitrogen assimilation, glutamine synthetase and glutamate synthase convert NH_3 into amino acids, providing plants and microorganisms with an accessible nitrogen source (Liu et al. 2019). In nitrogen heterotrophy, nitrifying bacteria such as *Nitrosomonas* and *Nitrobacter* transform NH_3 into nitrate through NH_3 monooxygenase and nitrite oxidoreductase; mostly encoded by *amoA*, NH_3 monooxygenase catalyzes the oxidation of NH_3 to hydroxylamine (Qiao et al. 2020). Concurrently, denitrifying microorganisms such as *Pseudomonas* and *Paracoccus* utilize nitrate, nitrite, nitric oxide, and N_2O reductases, encoded by *narG*/*napA*, *nirS*/*nirK*, and *nosZ*, to gradually reduce nitrate to nitrogen, reducing nitrogen loss and lowering greenhouse gas emissions (Min et al. 2012). Other microorganisms further contribute to nitrogen

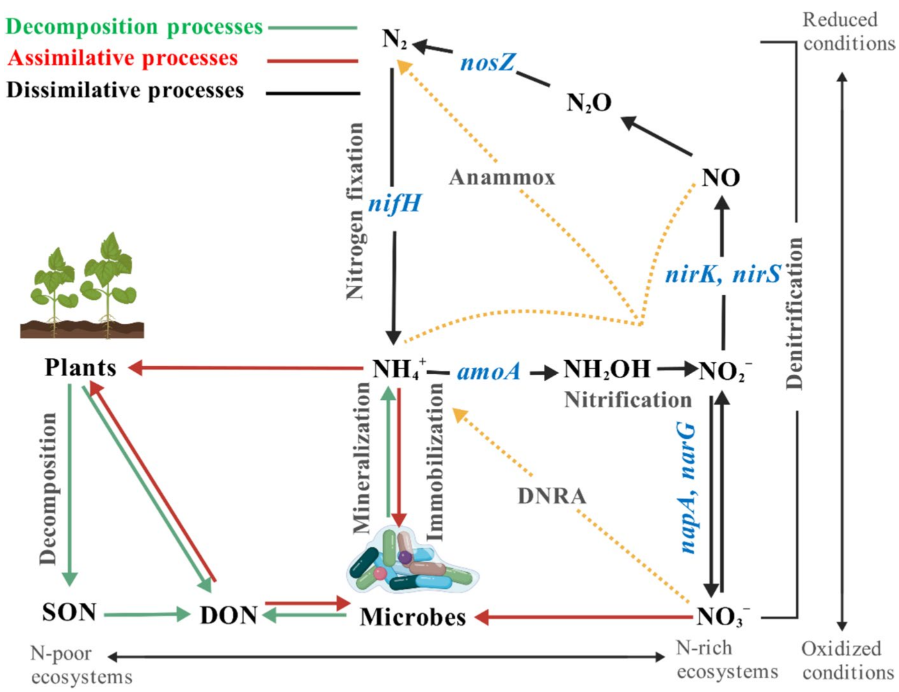

Fig. 3 The soil nitrogen cycle. The interactions between plants and microorganisms in the nitrogen cycle can be categorized into three main processes: decomposition (green arrows), assimilation (red arrows), and dissimilation (black arrows). Nitrogen (N_2) is converted to ammonium (NH_4^+), which is then transformed into nitrite (NO_2^-) and subsequently nitrate (NO_3^-) through a heterotrimeric enzyme pathway (black arrow). Plants absorb these nitrogen forms for growth, while dissolved organic nitrogen (DON) and soluble organic nitrogen (SON) are associated with both plant uptake and microbial conversion. This interconnected system highlights the essential roles of plants and microbes in sustaining nitrogen availability in ecosystems. *nifH*, *nosZ*, *nirK*, *nirS*, *amoA*, *napA,* and *napG* are key genes in the soil nitrogen cycling process

cycling by secreting enzymes such as chitinase and cellulase, which degrade organic matter, releasing organic nitrogen and promoting its mineralization (Levy-Booth et al. 2014; Meister et al. 2023). Overall, the synergistic effects of these genes, proteins, and enzyme activities enable microbial aggregates to efficiently regulate the soil nitrogen cycle, reducing nitrogen loss and improving nitrogen utilization efficiency.

2.5 Potential risks of microbial aggregates in mitigating soil nitrogen loss

The introduction or proliferation of microbial aggregates can significantly impact the structure of existing microbial communities (Zhao et al. 2024b), altering the diversity and composition of soil microbial communities, and potentially leading to a reduction in beneficial microbial populations and an increase in harmful ones (Liao et al. 2022). Li et al. (2024a) reported that introducing the exogenous rhizobacterium *Herbaspirillum* into rice pot soil inhibited the native diazotroph proteobacteria *Azospirillum*, resulting in increased rhizospheric NO_3^-–N and NH_4^+–N contents by 14.77% and 27.83%, respectively. Beneficial microorganisms are essential for promoting nutrient cycling, stimulating plant growth, and enhancing ecosystem resilience; in contrast, pathogenic microorganisms can threaten agricultural productivity, such as *Fusarium,* which can increase the incidence of crop diseases by 46.2% (Hayat et al. 2010; Huang et al. 2025).

Excessive introduction of exogenous microorganisms can place competitive pressure on native communities and disrupt ecological balance (Yang et al. 2022). Gu et al. (2020) observed that inoculated *P. aeruginosa* competed with native phosphate-solubilizing microbes for resources, inhibiting their activity by 56.5%, reducing soil phosphorus availability by 18.8%, and decreasing community diversity by

25.2% (Chen et al. 2024b). When exogenous microorganisms dominate resource acquisition, they compete with native microorganisms, decreasing community diversity and negatively impacting soil nutrient cycling and ecological stability (Wang and Kuzyakov 2024). Excessive introduction of exogenous microorganisms into organic waste composting can imbalance the composting microbial community, reducing composting efficiency and nutrient release (Wang et al. 2024c). While microbial aggregation contributes to nutrient cycling and enhances soil ecological functions, the potential risks associated with introducing exogenous microorganisms must be carefully evaluated to maintain the health and stability of soil ecosystems.

3 Common functional materials and their role in mitigating soil nitrogen loss

Functional materials are engineered substances designed with specific target properties (Goesmann and Feldmann 2010). Common functional materials, including biochar, nanomaterials, and organic polymers, possess specific functions and properties that have garnered significant attention recently due to their ability to promote soil nitrogen cycling, enhance soil nitrogen use efficiency, and reduce nitrogen loss (Fig. 4) (Fidel et al. 2018). Biochar application, as demonstrated in a meta-analysis of field studies, enhances the physicochemical properties of agricultural soils, creating an optimal habitat for nitrogen-fixing microorganisms (Ul Islam et al. 2021). In field trials, biochar application at rates of 0–40 t ha^{-1} significantly and progressively reduced nitrate leaching in the top 10 cm of soil, driving a corresponding 15.8% increase in maize yield per unit area under

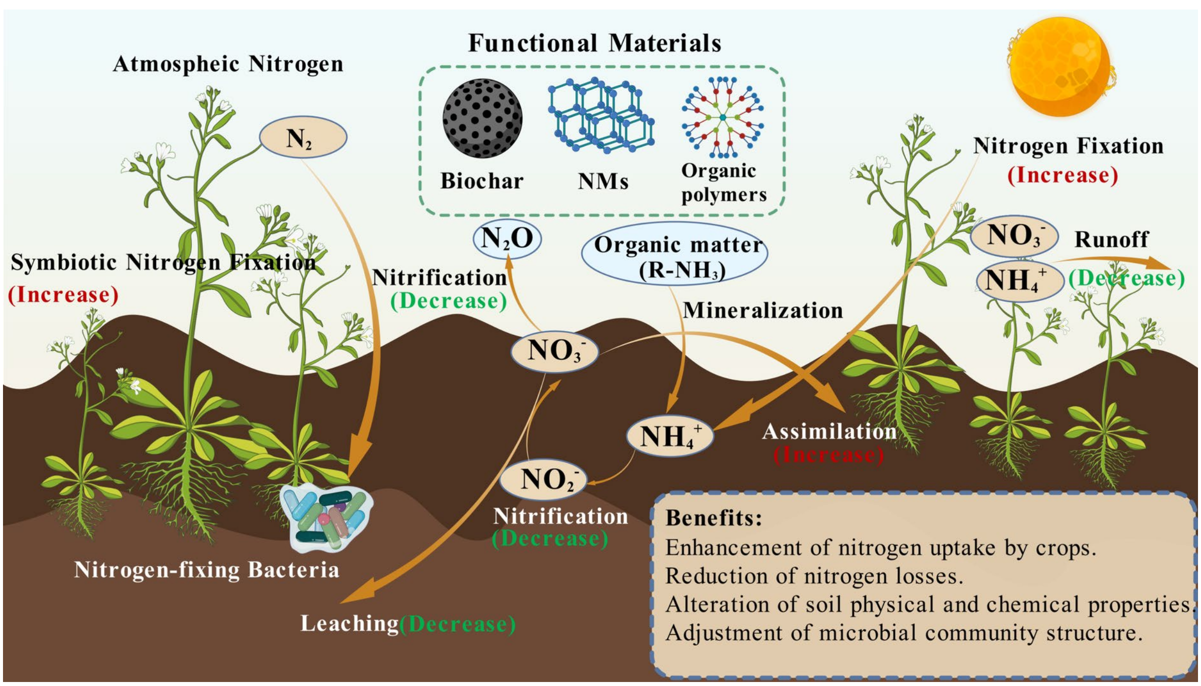

Fig. 4 The role of functional materials in the nitrogen cycle. The nitrogen cycle and the role of functional materials in nitrogen dynamics begin with atmospheric nitrogen (N_2), which can be fixed by nitrogen-fixing bacteria into forms usable by plants. Symbiotic nitrogen fixation allows plants to utilize fixed nitrogen for growth. Various processes are depicted, including nitrification, where ammonium (NH_4^+) is converted into nitrite (NO_2^-) and then nitrate (NO_3^-), and denitrification, which ultimately returns nitrogen to the atmosphere primarily as dinitrogen (N_2), with nitrous oxide (N_2O) as an intermediate byproduct. Organic matter plays a key role in the cycle, undergoing ammonification and assimilation by plants. Functional materials such as biochar, nanomaterials, and organic polymers have the potential to enhance soil nitrogen utilization and retention

nitrogen fertilization (Rahim et al. 2019). Application of 10 mg L^{-1} ferrite manganese nanoparticles significantly enhances the symbiotic nitrogen fixation of leguminous plants, increasing their nitrogen-fixing efficiency by 151.36% and ultimately driving a 25.70% increase in biomass accumulation (Ma et al. 2022b). Additionally, organic polymers can be used as coating materials for slow-release and controlled-release fertilizers to effectively regulate the rate of nutrient release. This functionality can extend the retention time of nitrogen in the soil, increasing nitrogen fertilizer utilization efficiency by 25.4%, and reducing nitrogen loss by up to 32.5% (Almutari 2023). These materials improve plant nitrogen uptake efficiency, ensuring that crops receive a continuous and balanced supply of nitrogen throughout their growth.

3.1 Biochar

Biochar, a carbon-rich material from biomass pyrolysis, enhances soil nitrogen retention through its functional groups (–COOH, –OH) that fix NH_4^+–N via cation exchange and hydrogen bonding, coupled with its micro- and mesoporous structure that provides extensive surface area for adsorbing various nitrogen forms and reducing leaching (Fan et al. 2018). In crops such as maize, these properties help maintain nitrogen levels in the root zone, supporting vigorous vegetative growth, particularly during early stages requiring high nitrogen supply (Tanure et al. 2019). However, unmodified biochar exhibits limited affinity for retaining NO_3^-–N; effective mitigation typically relies on using biochar with inherent anion exchange capacity or blending it with mineral composites to enhance nitrate adsorption (Leng et al. 2021). For instance, in vegetable cropping systems like tomatoes, where frequent irrigation exacerbates nitrate leaching, mineral-modified biochar has been demonstrated to significantly reduce nitrate nitrogen leaching while enhancing nitrogen uptake efficiency (Munera Echeverri et al. 2018; Zhao et al. 2024a). Sun et al. (2017) reported that biochar application reduced NO_3^-–N leaching by 13.2–29.7% and total nitrogen losses by 14.6–26.0%, contributing to more stable yields in cereal crop rotation systems.

Biochar application significantly alters soil physicochemical properties by increasing pH as well as soil water and organic carbon (SOC) content, while simultaneously reducing bulk density (Table 3) (Fig. 5) (Phillips et al. 2022; Wang et al. 2022b; Zhang et al. 2022b). A meta-analysis conducted by Singh et al. (2022) revealed that biochar significantly increased soil pH, cation exchange capacity, SOC content, and porosity by 46%, 20%, 27%, and 59%, respectively. Changes in soil physicochemical

Table 3 Biochar properties and experimental conditions from selected studies

Materials	Application rates (%)	Depths (cm)	Duration (days)	Specific surface area (m^2 g^{-1})	References
Reed biochar	0–8	0–50	120	406.00 ± 23.43	Zhang et al. (2022b)
Cow dung biochar	1–5	10–20	90	185.50 ± 12.10	Gao et al. (2019)
Corn stover biochar	2–6	0–15	150	312.70 ± 18.90	Singh and Mavi (2018)
	1–4	5–15	180	520.30 ± 30.50	Xie et al. (2021)
	0.5–3	0–10	365	450.20 ± 25.80	Novak et al. (2010)
	2–5	10–30	240	398.60 ± 20.40	Zavalloni et al. (2011)
Wheat straw biochar	1–7	0–20	110	355.40 ± 22.10	Phillips et al. (2022)
	0.5–4	5–15	200	480.00 ± 28.30	Manirakiza et al. (2019)
Rice straw biochar	2–8	0–15	180	265.80 ± 15.70	Novak et al. (2010)
Apple branch biochar	1–5	10–25	100	290.50 ± 16.20	Wang et al. (2022b)
	1–3	0–10	270	510.75 ± 32.15	Ball et al. (2010)
Rice husk biochar	3–9	0–20	120	220.90 ± 11.80	Tan et al. (2015)
Straw biochar	1–6	0–15	150	340.60 ± 19.40	Cayuela et al. (2014)
	2–5	5–20	90	105.30 ± 8.50	Munera-Echeverri et al. (2022)
	1–4	0–15	180	580.20 ± 35.00	Liu et al. (2020)

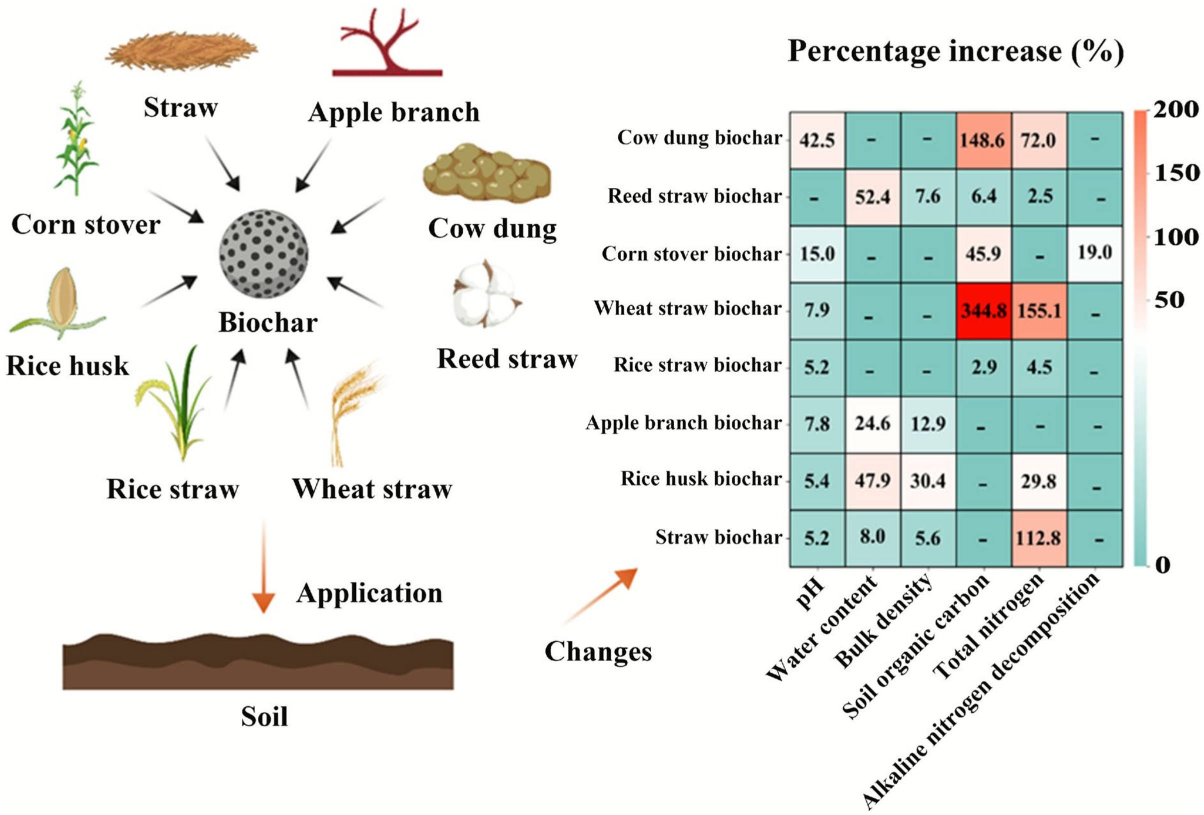

Fig. 5 Effect of biochar application on soil physicochemical properties. The effects of various biochar types on the main physicochemical properties of soil are shown, providing a reference for understanding its agricultural benefits. Eight biochar types are shown, ranging from cow dung to rice husk, showing their different sources and their resulting changes in physicochemical parameters, including soil pH (power of hydrogen), water content, bulk weight, soil organic carbon, total nitrogen, and alkaline dissolved nitrogen after application. These data highlight the potential of biochar as an effective amendment for improving soil health and fertility. "-" indicates that the data was not documented. Averaging data across multiple groups

properties are key mechanisms by which biochar mitigates soil nitrogen loss and enhances total nitrogen content (Zheng et al. 2013). Although the increased pH and SOC content can promote niturifying bacteria, biochar concurrently reduces N_2O emissions by shifting the end product of denitrification from N_2O towards N_2. This shift is driven by the elevated pH and abundant organic carbon, which enable denitrifying bacteria (e.g., *Pseudomonas*, *Paracoccus*) to complete the reduction process (Liu et al. 2016b, 2021b; Tariq et al. 2024). The enhanced cation exchange capacity facilitates more efficient capture of nitrogen, reducing its loss through leaching (Yu et al. 2017). Improved porosity promotes uniform water distribution, ensuring efficient absorption of nitrogen by plant roots (Wang and Smith 2004). Together, these biochar-induced alterations in soil physicochemical properties inhibit nitrogen loss and reduce root growth resistance, promoting plant root growth and development; a meta-analysis conducted by Xiang et al. (2017) found that biochar application significantly increased root biomass, volume, surface area, length, and the number of root tips by approximately 32%, 29%, 39%, 52%, and 17%, respectively. This phenomenon is consistently observed in staple cereals like maize and wheat, which develop deeper and more extensive root systems for improved water and nutrient foraging, as well as in legumes such as soybean, where enhanced root proliferation supports greater nodulation and nitrogen fixation potential (Eissenstat and Yanai 1997; Herath et al. 2013). Biochar also reduces the emission of N_2O from the soil by approximately 54% by altering the structure of the soil microbial community, which influences enzyme activity and regulates gene expression. The application of biochar significantly affects the abundance of various soil microorganisms, including ammonia-oxidizing archaea, ammonia-oxidizing bacteria, and nitrifying bacteria (Sun et al. 2024). In addition, total nitrogen, NO_3^-–N, and NH_4^+–N contents as well as the abundance of denitrification-related genes in soil are significantly positively correlated with biochar application (Li et al. 2020). Overall, biochar holds significant potential for improving soil nitrogen management and advancing sustainable agricultural practices.

3.2 Nanomaterials

Effective crop nitrogen utilization is essential for reducing soil nitrogen loss, which is contingent upon the availability of nitrogen in the soil as well as the transport capacity and nitrogen demand of the plants (Hirel et al. 2011; Huang et al. 2023). Nanomaterials modulate microbial processes to enhance soil nitrogen availability, with rhizosphere microbes playing a pivotal role in plant nitrogen uptake (Yang et al. 2024a). Zhang et al. (2020) demonstrated that Fe_3O_4 nanoparticles increased the relative abundance of *Burkholderia-Paraburkholderia* by 38.7%, resulting in a 22.4% enhancement in plant nitrogen uptake compared to the control. Nano-nitrogen fertilizers can reduce soil nitrogen release rates by 40–60% and decrease nitrogen loss through NH_3 volatilization and nitrate leaching, improving crop nitrogen use efficiency by 18–25% (Kottegoda et al. 2017). Alimohammadi et al. (2020) found that nano-nitrogen fertilizers increased sugarcane sucrose yield by 18.2% at equivalent nitrogen inputs to traditional urea fertilizers (150 kg N ha^{-1}), with nitrogen use efficiency reaching 54.1%. Similarly, Saad et al. (2022) reported that foliar application of 14 L ha^{-1} green chitosan nanoparticles combined with 120 kg ha^{-1} of mineral nitrogen fertilizer effectively increased nitrogen use efficiency in wheat by 28.5% and reduced nitrogen loss by 34.7%; a 19.3% increase in chlorophyll content and a 22.1% increase in grain yield were also observed.

Nanomaterials regulate soil nitrogen loss by enhancing symbiotic nitrogen fixation in legumes and synergizing with microbial aggregates (Zhang et al. 2024d). The Ce^{3+}/Ce^{4+} redox pair in cerium dioxide nanoparticles scavenges 89.2% of rhizobial reactive oxygen species within 6 h, preserving 92.4% of nitrogenase activity after 72 h of exposure, extending the active nitrogen fixation cycle of *Rhizobium* by 22.5% compared to untreated systems (Kottegoda et al. 2017). $CoFe_4$ nanoenzymes exhibit potent peroxidase and superoxide dismutase mimetic activities, which play a key role in scavenging reactive oxygen species and promoting the growth of rhizobial bacteria (Ma et al. 2022a). Reactive oxygen species accumulation destroys the structure and function of nitrogen-fixing enzymes; nanomaterials effectively scavenge these through their antioxidant properties, reducing the damage to rhizobia caused by oxidative stress (Khan et al. 2023). Carbon dots enhance nitrogen-fixing enzyme activity by 38.2% in soybean (*Glycine max* L.) rhizomes under drought conditions by facilitating electron transfer (Wang et al. 2018a). Legume symbiotic nitrogen fixation efficiency is regulated by specific genes; these, particularly *NIN* (which regulates nodule formation), can be upregulated by multi-walled carbon nanotubes, to promote nodule development and enhance nitrogen fixation efficiency by 28–45% (Yuan et al. 2017).

Nitrogen transformation in soil is a complex process involving numerous microbial activities and chemical reactions. Plants absorb nitrogen as NH_4^+–N and NO_3^-–N through various processes, including nitrogen fixation, ammonification, nitrification, and denitrification (Kuypers et al. 2018; Wang et al. 2022a). Nanomaterials significantly influence soil microbial communities and nitrogen transformation; fullerene inhibits anaerobic NH_3 oxidation, multi-walled carbon nanotubes inhibit both NH_3 oxidation and denitrification, and graphene and carbon black inhibit nitrate reduction (Ge et al. 2018; Zhang et al. 2020). The aforementioned nanomaterials, which include copper oxide (CuO), silver (Ag), zinc oxide (ZnO), silicon dioxide (SiO_2), and iron oxide (Fe_3O_4) nanoparticles, enhance the abundance of nitrogen-fixing microorganisms by 25–68% (Asadishad et al. 2018). Nanomaterials also exert a considerable influence on enzyme activity; for example, Fe_2O_3 nanoparticles have been observed to increase urease activity by 45.2%, while carbon dots and CuO nanoparticles can inhibit nitrate reductase activity by 32–55%, effectively reducing NO_3^-–N denitrification losses by approximately 40–65% compared to untreated controls (He et al. 2011; Huang et al. 2024). In summary, the application of nanomaterials presents a novel strategy for optimizing crop nitrogen management that enhances effective utilization by crops, reduces environmental risks, and promotes sustainable agricultural development.

3.3 Organic polymers

Organic polymers are primarily utilized as coating materials for slow and controlled-release fertilizers in modern agriculture (Vejan et al. 2021). In recent years, petroleum-based polyurethanes have become prominent due to their cost-effectiveness, wide availability, non-toxicity, and biodegradability (Kassem et al. 2024). Additionally, vegetable oil-based polyurethanes, particularly those from castor and soybean oil, have garnered increasing attention owing to their environmental benefits and low cost. These organic polymers effectively regulate the nutrient release rate from fertilizers through diffusion, solubility, and reaction control (Du et al. 2006). Diffusion control is contingent upon the coating pore structure and thickness, which determine the diffusion path length for water and nutrients. Solubility control pertains to the gradual dissolution of certain coatings upon contact with water, releasing encapsulated nutrients (Bortoletto et al. 2020). Reaction control involves the design of specific polyurethane coatings that undergo chemical reactions only under certain conditions (Priya et al. 2024). Overall, polyurethane coatings show great potential for optimizing fertilizer performance and improving agricultural efficiency (Noreen et al. 2016).

Organic polymers have demonstrated exceptional outcomes in practical applications (Vejan et al. 2021). The utilization of slow and controlled-release fertilizers significantly enhances plant nitrogen uptake efficiency, ensuring that crops receive a continuous and balanced supply of nitrogen throughout their growth cycle and mitigating nitrogen loss due to over-fertilization (Salimi et al. 2024). Bortoletto et al. (2020) found that inorganic nitrogen content in soil treated with slow-release fertilizers during autumn was 25–40% higher than that observed with conventional application methods. Wu et al. (2018b) reported that these fertilizers not only elevated the levels of NH_4^+–N in tea plantation soils but also effectively reduced nitrogen loss, achieving a nitrogen utilization rate of 55%. Mi et al. (2019) found that after a continuous application over 7 days, the concentrations of NH_4^+–N and NO_3^-–N in the 0–60 cm soil layer were increased significantly by 62% and 48%, respectively, under sulfur plus resin-coated urea treatment compared with those under split-application urea treatment. This fertilizer not only improved the physical and chemical properties of the soil but also enhanced its water and nutrient retention capacity, further diminishing nitrogen loss (Almutari 2023). Slow-release fertilizers enhance soil nitrogen conversion efficiency by promoting the proliferation of nitrogen-fixing bacteria and boosting urease activity, thereby fostering beneficial microbial communities (Su et al. 2021). Although the rise in urease activity poses a challenge by potentially boosting NH_3 volatilization, the core mechanism of controlled nutrient release effectively limits the substrate available for such loss (Soares et al. 2012). This key feature, along with mitigation of nitrate leaching, results in a net decrease in total nitrogen loss from the soil system (Salimi et al. 2023).

Overall, functional materials have demonstrated significant potential for reducing soil nitrogen loss and improving nitrogen utilization efficiency through various mechanisms. However, certain limitations remain (Table 4). In practical applications, it is essential to optimize application methods to further enhance their effectiveness in minimizing nitrogen loss. The quantity and timing of functional material application can be tailored to specific soil types, crop requirements, and climatic conditions, utilizing precision agriculture techniques to achieve optimal outcomes. Additionally, integrating different types of functional materials can maximize their respective advantages and create synergistic effects, further enhancing their benefits in nitrogen management.

3.4 Potential risks of functional materials in mitigating soil nitrogen loss

Functional materials typically possess a long half-life in soil, and their prolonged accumulation may adversely affect soil structure and function (Xu et al. 2014). Harmful substances found in biochar include heavy metals, polycyclic aromatic hydrocarbons, volatile organic compounds, and other potential pollutants, which can accumulate and negatively impact soil microbial activity (Godlewska et al. 2021).

Table 4 Effectiveness of different functional materials in reducing nitrogen loss

Functional material type	Mechanisms of action	Advantages	Limitations	References
Biochar	Adsorption and fixation to reduce nitrogen leaching and volatilization	Enhances the physical and chemical properties of the soil	May alter soil pH at higher application rates	Waheed et al. (2025)
	Improvement of soil structure by enhancing soil water and nutrient retention capacity	Increases biological activity within the soil	Higher energy consumption during production	Agyekum and Nutakor (2024)
	Promotes the growth of beneficial microorganisms	Low cost and environmentally friendly	Effectiveness is affected by raw materials and preparation methods	Lefebvre et al. (2024)
Nanomaterials	Regulates microbial activity and increases the relative abundance of nitrogen-fixing bacteria	Increases plant nitrogen uptake efficiency	Long-term safety requires further investigation	Sharma et al. (2025)
	Improves soil physicochemical properties and enhances nitrogen retention capacity	Reduces environmental nitrogen loss	Higher costs associated with production	Nagime and Chandak (2024)
	Controls fertilizer release rates to reduce nitrogen volatilization and leaching	Enhances the biological activity of the soil	May negatively impact non-target organisms	Tian et al. (2025)
Organic polymers	Diffusion control: pore structure and thickness determine the length of diffusion paths for water and nutrients	Extends the retention time of nitrogen in the soil	Degradation characteristics may have long-term effects	Zhou et al. (2025)
	Dissolution control: the coating slowly dissolves in contact with water, releasing nutrients	Reduces surface nitrogen leaching due to rainfall or irrigation	Higher initial cost	Wang et al. (2019a, b, c)
	Reaction control: chemical reaction under specific conditions to release nutrients	Promotes the development of healthy microbial communities	Requires optimization of coating thickness and structure	Chowdhury et al. (2022)

Key functional materials used to improve nitrogen retention in agricultural soils are summarized, comparing their mechanisms of action, advantages, and limitations. Biochar enhances soil structure and microbial activity but may alter pH, while nanomaterials boost nitrogen uptake efficiency but require long-term safety assessments. Organic polymers control nutrient release through diffusion, dissolution, or reactions, but face challenges related to cost and degradation

Additionally, toxic chemicals adsorbed by biochar can be desorbed under specific conditions, harming soil microbes and affecting overall soil health and functionality (He et al. 2021).

While nanomaterials have shown promise in enhancing soil functionality, nanoparticle release and transformation may lead to their aggregation and the formation of toxic substances that adversely affect soil microorganisms and plant growth following long-term accumulation (He et al. 2023). The accumulation of titanium dioxide nanoparticles in soil (> 50 mg/kg) significantly inhibits soil microbial activity and is toxic to nitrogen-fixing and ammonia-oxidizing bacteria, decreasing soil nitrogen cycling efficiency (Kaur et al. 2022). Ge et al. (2014) found that the introduction of nanomaterials into agricultural soils may threaten microorganisms involved in nitrogen turnover, depending on size, dosage, type, exposure duration, and soil type. Nanosilver significantly inhibits its soil microbial respiration and enzymatic activities at a low dose (10 mg/kg); at a high dose (100 mg/kg), it induces significant changes in microbial community structure (Yonathan et al. 2022). Metal-based nanomaterials releasing Zn^{2+} at a concentration of approximately 20 mg/kg were toxic to microbial cells, inducing a 3.5-fold increase in microbial intracellular reactive oxygen species and causing physical and oxidative stress (Suresh et al. 2013). Shen et al. (2015) found that zinc ions released from zinc oxide nanoparticles in soil significantly reduced microbial activity by causing loss of cell membrane integrity and inducing oxidative stress.

Organic polymers used as soil functional materials hold potential for enhancing nitrogen fixation by improving water retention and microbial habitat stability (Chang et al. 2025). However, their long-term application may pose ecological risks, including the unintended enrichment of denitrifying bacteria, which can shift nitrogen cycling toward N_2O emissions (Huang et al. 2020). Polyethylene glycol (PEG) exhibits limited biodegradability in certain soil environments, leading to its persistence and potential accumulation, which may alter soil structure by reducing macroporosity and impeding root penetration (Abdalla et al. 2005). Moreover, monomers or decomposition byproducts (e.g., acrylamides) may exhibit toxicity to diazotrophic microbes or plants. Interactions with native organic matter could also alter the bioavailability of nutrients and trace metals (Rychter et al. 2019). In heterogeneous soil environments, uneven polymer distribution may create localized anoxic zones, promoting incomplete denitrification (Lucas et al. 2024).

Overall, while functional materials can significantly enhance soil quality and crop productivity, it is essential to carefully consider their long-term accumulation and the potential toxicity of their degradation products. A comprehensive assessment of their usage must be performed to ensure that their benefits are not compromised by their toxicity and accumulation to support sustainable soil management and ecological conservation.

4 Microbial aggregates synergize with functional materials to mitigate soil nitrogen loss

In addition to preventing nitrogen loss in soil ecosystems, the synergistic interactions between functional materials and microbial aggregates significantly influence microbial growth, reproduction, and metabolism (Fig. 6) (Lv et al. 2024). The favorable surface properties of functional materials promote microbial attachment and biofilm formation, enhancing their stability and persistence (Zhang et al. 2024a). Microbial aggregates, in turn, enhance the stability of functional materials by secreting extracellular polymers; they can also utilize the carbon and energy sources provided by the materials for growth and metabolism (Velarde et al. 2023). The application of functional materials also improves soil structure and nutrient availability, with significantly enhanced nitrogen retention compared to the use of microorganisms alone (Wu et al. 2021). This synergistic effect is accomplished through multiple mechanisms, including physical, chemical, and biological interactions.

4.1 Physical interaction

Functional materials play a pivotal role in facilitating microbial aggregation through tailored surface properties and microenvironment optimization (Di et al. 2025; Ye et al. 2025). Microbial colonization is enhanced by high-surface-area substrates with specific physicochemical characteristics (Martienssen and Schöps 1999). Martinov et al. (2010) found that the specific surface area of up to 1800 m^2/g of a polyethylene and vinyl acetate copolymer significantly

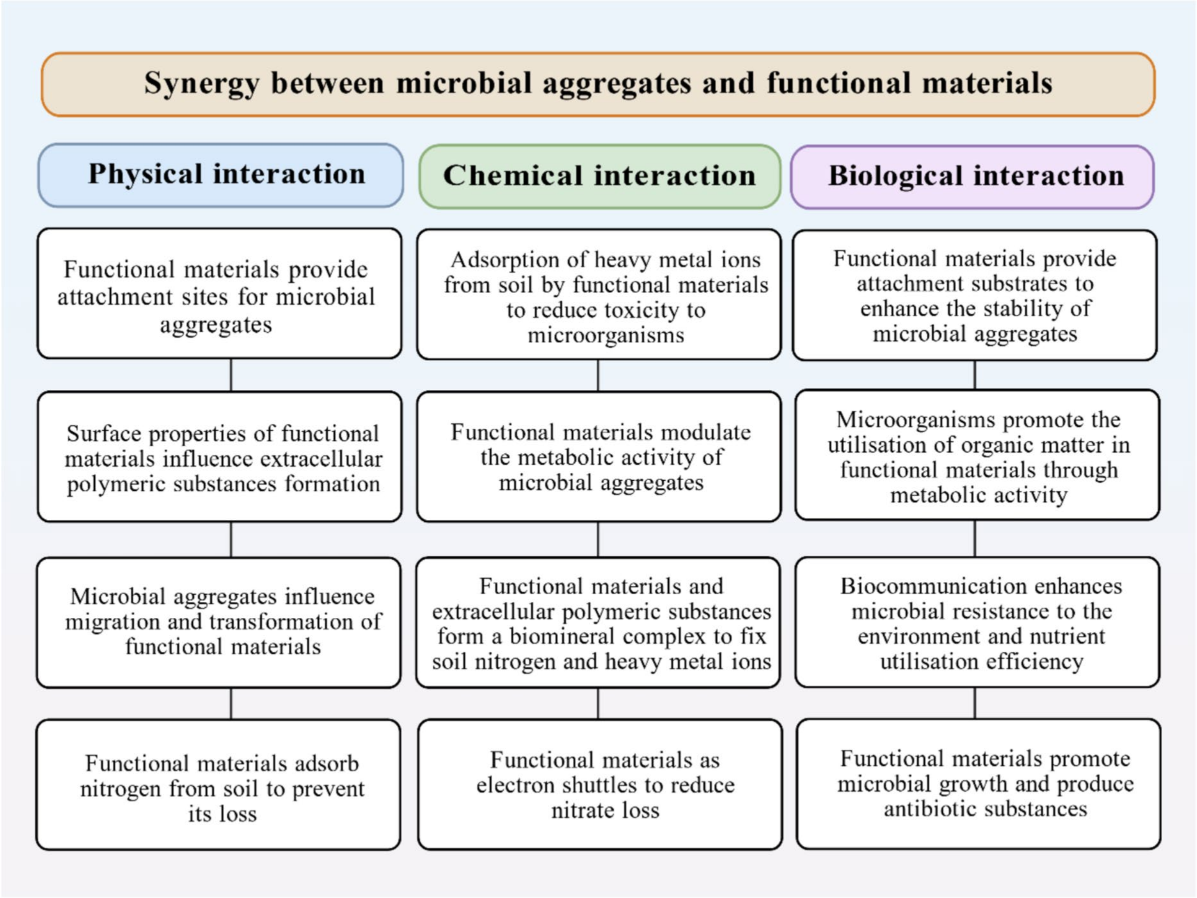

Fig. 6 The synergy between functional materials and microbial aggregates in soil. The synergies between microbial aggregates and functional materials can be categorized into three interaction types: physical, chemical, and biological. The multiple mechanisms by which functional materials and microbial aggregates synergize to prevent soil nitrogen loss are also detailed

enhanced microbial adhesion by 3.8-fold; this enabled denitrifying bacteria to reduce soil NO_3^-–N leaching and N_2O emissions through sequential enzymatic reduction at the aerobic-anaerobic interface (Bano et al. 2024). The porous structure of functional materials supports microbial colonization and physical trapping of nitrogen compounds, but mitigating nitrate leaching requires material modification for anion exchange to electrostatically retain nitrate ions (Einsiedl and Mayer 2006; Gu 2007). Since the surface charge of most microbial cells is typically negative, functional materials with a positive charge can effectively promote cell attachment or aggregation (Metwally and Stachewicz 2019). The electrostatic interaction between a positively charged functional material and a negatively charged microbial cell membrane increased NH_4^+ adsorption 42.3 mg/g, 3.1-fold higher than that of a neutral material (13.7 mg/g), forming a localized nitrogen reservoir available to the nitrifying bacteria (Larsen et al. 2008).

The surface properties of functional materials, including their roughness, charge, porosity, and hydrophobicity, significantly influence biofilm formation. Hydrophobicity is directly linked to microbial adhesion, as most bacteria tend to attach to hydrophobic surfaces (Ercan and Demirci 2015). In loamy clay soils amended with rice straw biochar (0–10%), although its application only marginally increased the content of available nitrogen, phosphorus and potassium, DNA derived from manure and root exudates was still efficiently adsorbed onto the hydrophobic biochar surface via π-π interactions and hydrophobic partitioning (Al Masud et al. 2023). The structural complexity of biochar provides dual advantages. Its surface offers abundant binding sites for microbial attachment and inhibitor detoxification. Biochar can also adsorb toxic substances such as heavy metals and organic pollutants; its saturated adsorption of cadmium can reach 89.4 mg/g, reducing the effective state of cadmium in soil by 62–75%. This helps to maintain the activity and diversity of microbial communities associated with the nitrogen cycle (Lu et al. 2020; Sun et al. 2020b). Additionally, the distorted pore network of biochar physically limits oxygen diffusion to create anoxic microsites (dissolved oxygen < 0.5 mg/L). This inhibits nitrification and enhances symbiotic activity, effectively transferring nitrogen to microbial assimilation rather than gas loss (Li et al. 2025). The formation of biofilms can be effectively accelerated by modulation of functional material surface properties to enhance microbial aggregate stability and functionality (Hadjiev et al. 2007).

Microbial aggregates also significantly modulate the behavior of functional materials in soil. By promoting biofilm formation, microbial aggregates increase the stability of biochar in soil, prolonging its persistence by 2–threefold (Ajeng et al. 2023; Wang and Kuzyakov 2024). In laboratory studies of microenvironments, EPS acts as a flocculant, binding biochar particles to form a physical barrier. Results indicate that this flocculation reduces the decomposition rate of biochar and minimizes NH_3 volatilization compared to non-flocculated systems (Fan et al. 2024; Li et al. 2023; Zhang et al. 2006). Microbial aggregates have reduced nanoparticle diffusion distance and leaching loss through EPS-mediated trapping (pore size: 0.2–5 μm) (Khan et al. 2022; Yang et al. 2024a). Zhong et al. (2024) reported that the addition of biochar increased the relative abundance of Actinobacteria in an artificial wetland by 2.3-fold, and the percentage of nitrogen-fixing *Duganella* increased from 5.4 to 12.7%. Foley et al. (2011) discovered that iron oxide nanoparticles (50 mg/kg) stimulated increase in *Streptomyces* growth and a 3.1-fold enhancement in *Nocardioides* 16S rRNA gene copy number in soil microcosms. These findings confirm that microbial aggregates effectively modulate the environmental behavior of functional materials through physical synergies.

Strategic manipulation of functional material properties offers transformative potential in sustainable agriculture and environmental engineering. Optimizing biochar hydrophobicity and porosity profiles could simultaneously increase soil nitrogen fixation, reduce nitrogen loss, and promote beneficial microbial consortia. Additionally, nanomaterial design incorporating microbial trapping mechanisms may enable targeted delivery of soil amendments while minimizing ecotoxicological risks.

4.2 Chemical interaction

Chemical interactions between microbial aggregates and functional materials play a crucial role in influencing microbial metabolic pathways and nitrogen conversion efficiency through interactions between material surfaces and extracellular polymers secreted by microorganisms to form stable complexes that enhance microbial activity and reduce nitrogen loss (Peixoto et al. 2024; Rajput et al. 2023). Extracellular polymers are primarily composed of polysaccharides, proteins, nucleic acids, and lipids; these contain numerous functional groups, including carboxyl, hydroxyl, amino, and phosphoryl groups, which can interact with the surfaces of functional materials (Kayoumu et al. 2025). Priyadarshanee and Das (2024) revealed that carboxyl and hydroxyl groups on biochar can bind to polysaccharides and proteins in extracellular macromolecules through hydrogen bonding or electrostatic interaction to form a stable biomineral complex; this complex increased the nitrogen-fixing enzyme activity of rhizobia to 1.9 μmol C_2H_4/h-mg protein while increasing soybean nitrogen accumulation (Du et al. 2021). *Rhizobium* were able to fix nitrogen more efficiently and reduce dependence on exogenous fertilizers under the protection of a bio-mineral complex; additionally, the nitrate reduction efficiency of *P. aeruginosa* was increased, reducing nitrate leaching and N_2O emissions (Chen et al. 2024a).

Microbial immobilization on functional materials reduces the toxicity of heavy metals and protects the activity of nitrogen-fixing, nitrifying, and denitrifying bacteria; it also minimizes the potential for heavy metals to migrate through the soil to the plant root system (Priyadarshanee and Das 2024). The efficacy of bio-mineral complexes stems from their dual action: alleviating heavy metal toxicity through pH-dependent precipitation and complexation to reduce bioavailability, thereby enhancing microbial nitrogen fixation and, through this genuine improvement in N-cycling as well as carbon input, synergistically improving soil fertility (Maity et al. 2022). The chemical interactions between microbial aggregates and functional materials play a significant role in nitrogen cycling. Yuan et al. (2022) demonstrated that functional materials such as biochar, carbon nanotubes, and graphene can act as electron shuttles to increase nitrate reduction to 1.8 μmol/(h-mg protein) while reducing soil NO_3^-–N leaching by 55.6%. Due to their unique electronic structure and large specific surface area, these materials can effectively transfer electrons between the microbial outer cell membrane and pollutants, accelerating biochemical reactions (Yuan et al. 2022). Wei et al. (2022) found that nitrifying and denitrifying bacteria in microbial aggregates with these functional materials achieved nitrification–denitrification coupling, optimizing the nitrogen cycling process with an efficiency as high as 89.4% while reducing N_2O emissions by 63.5% as well as other gaseous nitrogen loss.

In summary, the chemical interactions between microbial aggregates and functional materials create an environment conducive to microbial growth, promoting metabolic activities and enhancing nitrogen conversion efficiency. Additionally, these interactions improve soil structure and fertility by forming stable bio-mineral complexes that effectively immobilize heavy metals and reduce their ecological risks. This synergy provides strong support for their application in sustainable agriculture and environmental protection.

4.3 Biological interaction

As previously stated, functional materials can be used as attachment substrates for microorganisms, enhancing microbial aggregate formation and stability (Costa et al. 2018). Mixing biochar into coarse-textured soil (0–20 cm) optimized the soil water and air environment by increasing total porosity by 12.3% and raising field capacity and effective water-holding capacity to 23.8% and 25.6%, respectively. This improved microhabitat, combined with the input of recalcitrant organic matter and bioavailable micronutrients (K, Ca, Zn) from biochar, promoted microbial aggregate formation. This process stabilized and released nutrients gradually, ultimately significantly increasing plant available nitrogen (NH_4^+–N + NO_3^-–N) levels and phosphorus use efficiency (grain yield per unit of available phosphorus) compared to the control group (Wei et al. 2023; Wu et al. 2018a). In sandy soil improvement, applying 4% biochar to the plow layer yielded the best results (Pu et al. 2019). Microorganisms further contribute to nutrient cycling by converting the complex organic matter in biochar into forms that are more readily absorbed by plants, such as small-molecule organic acids, amino acids, and sugars (Bolan et al. 2023). Microbial enzymes facilitate the degradation and conversion of organic polymers, providing energy and carbon sources for the microorganisms along with available nutrients for the soil ecosystem (Priyadarshanee et al. 2023).

Functional materials significantly promote microbial degradation efficiency of organic pollutants through enhanced electron transfer, in addition to playing a key role in regulating soil nitrogen loss (Kayoumu et al. 2025). As electron shuttles, functional materials can mediate electron transfer between microorganisms and organic pollutants, accelerating degradation while optimizing key nitrogen cycling pathways (Mosley et al. 2022). Conductive materials such as iron oxide and graphene increase the metabolic activity of the denitrifying bacterium *P. aeruginosa* by facilitating electron transfer between cells and the pollutants through their high electrical conductivity (Kang et al. 2021); this increases the degradation efficiencies of a wide range of organic pollutants, including polycyclic aromatic hydrocarbons, pesticides, petroleum hydrocarbons, chlorinated organics, and industrial chemicals (Mgadi et al. 2024). This enhanced electron transfer also facilitates the reduction of nitrate to nitrogen, reducing nitrate leaching and reducing N_2O emissions, as well as reducing gaseous nitrogen loss (Liu et al. 2024). This improves microbial soil nutrient utilization efficiency and increases their resistance to environmental stresses, improving microbial survival under adverse environmental conditions (Yang et al. 2024b).

Functional materials can induce microorganisms to produce antibiotics that inhibit the growth of soil pathogens, protecting plants from soil-borne diseases (Tyc et al. 2014). Nanohydroxyapatite treatment enhanced actinomycin production by *Streptomyces* sp. by 3.2 μg/g of soil, inhibiting *Fusarium spinosum* by 78.5% (Zhao et al. 2021a). In biological nitrogen fixation, biochar has been used as a carrier to increase the colonization density of *B. japonicum* by 2.5-fold, increasing nitrogen-fixing enzyme activity to 1.8 μmol C_2H_4/ (h-mg protein) (Chang et al. 2025). The synergistic effect of functional materials and microorganisms provides an efficient solution to reduce nitrogen loss, improve soil fertility, and achieve sustainable agricultural practices.

5 Advantages of microbial aggregates with synergistic functional materials for mitigating soil nitrogen loss

The synergistic application of microbial aggregates and functional materials has significant advantages in reducing soil nitrogen loss (Fig. 7). By improving the nitrogen fixation efficiency, the activity of nitrogen-fixing bacteria is significantly enhanced, increasing the available nitrogen in the soil (Lv et al. 2024). This synergistic effect fosters a stable micro-ecological environment. It mitigates inter-microbial competitive pressure by providing diverse ecological niches, while concurrently controlling nutrient release kinetics to match plant uptake patterns (Ali et al. 2021; Liao et al. 2022). This dual action ensures a more balanced nutrient availability for crops (Sun et al. 2025). Functional materials also control nutrient release rates, further enhancing the resistance and activity of microorganisms to more effectively prevent nitrogen loss and promote long-term soil fertility (Sharafinia et al. 2025).

5.1 Improving nitrogen fixation efficiency

Rhizobium, which is symbiotic with legumes, converts atmospheric nitrogen into plant-available ammonium-nitrogen along with native nitrogen-fixing bacteria (Aasfar et al. 2021; Brambilla et al. 2024). Functional materials can enhance this process. Biochar improves soil aeration and water retention

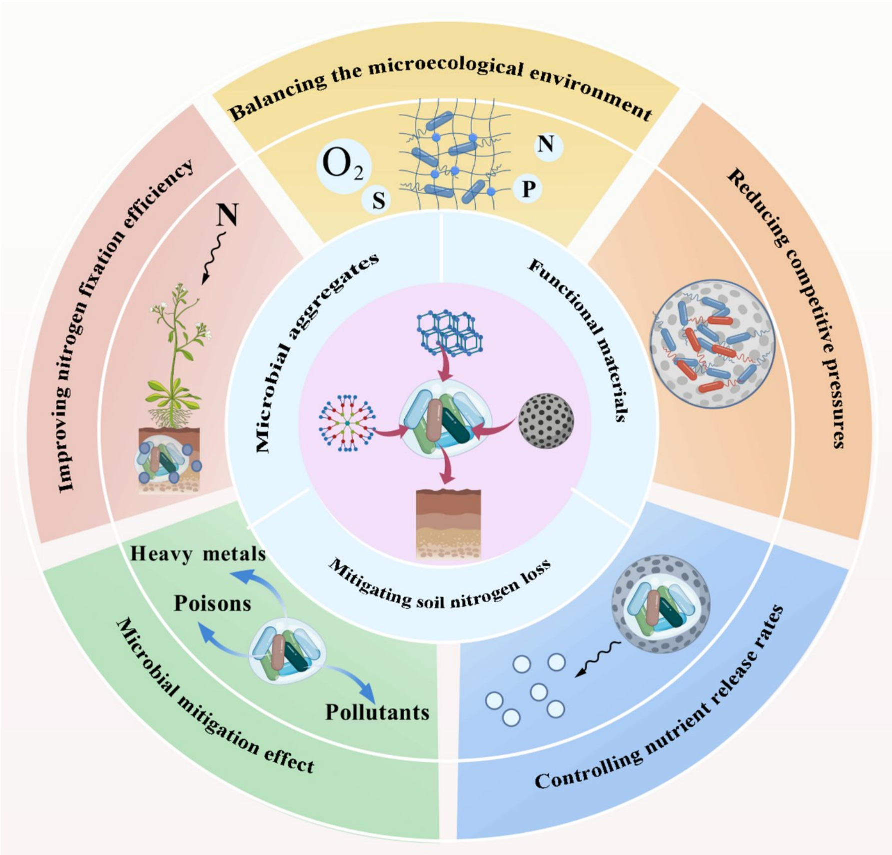

Fig. 7 Advantages of the synergistic functions of microbial agglomerates with functional materials in reducing soil nitrogen loss

through its porous structure, creating an ideal habitat for nitrogen-fixing microorganisms and increasing soybean nitrogen-fixing enzyme activity; additionally, its surface functional groups adsorb ammonium ions, reducing NH_3 volatilization (Lin et al. 2023a; Wu et al. 2022). Nanomaterials such as silica can triple the number of nitrogen-fixing bacteria and increase nitrogen utilization through regulation of soil pH and redox potential; their unique surfaces can also activate nitrogen-fixing enzyme activity (Bekkam and Thiyagarajan 2024; Chen et al. 2024c). Slow-release functional materials such as poly-coated urea increase corn yield while reducing nitrogen loss by controlling the rate of nitrogen release (Dhakal and Nelson 2019); this matches the dynamics of microbial nitrogen uptake, avoiding nitrogen leaching at the beginning of fertilization while providing a continuous source of nitrogen for subsequent microbial nitrogen fixation (Ghafoor et al. 2021; Lee and Ku 2025; San Le et al. 2022). Applied at 2% (w/w), clay minerals maintain field-observed nitrogen fixation efficiency above 45% under drought via ammonium immobilization, while 0.5% (w/w) temperature-responsive polymers preserve laboratory-measured activity exceeding 90% at low temperatures by protecting microbial aggregates (Ji et al. 2024; Mamo et al. 1993).

The synergistic effects of functional materials and microbial aggregates reduce nitrogen loss through three key pathways: adsorption of biochar and clay minerals reduces ammonium-nitrogen volatilization and nitrate-nitrogen leaching, nanomaterial-promoted denitrification converts nitrate-nitrogen to nitrogen gas and reduces N_2O emissions, and slow-release coatings achieve a precise match between nitrogen supply and crop demand. Field trials have shown that this combined strategy can increase nitrogen utilization by 32–65% while reducing environmental losses by 38–50%, providing a reliable solution for sustainable agriculture (Wani et al. 2022).

5.2 Balancing the micro-ecological environment

Beneficial microorganisms play a critical role in soil ecosystems, promoting nutrient cycling, facilitating plant growth, and enhancing ecosystem resilience (Marzouk et al. 2025). Suitable microbial aggregates can enrich soil microbial diversity, establishing a healthy microbial community structure and inhibiting the growth of harmful microorganisms to maintain soil ecosystem stability (Chen et al. 2024b). The introduction of composite microbial aggregates increased the Shannon diversity index of soil microorganisms from 4.8 to 6.3, while reducing the abundance of the soilborne pathogen (Steen et al. 2010). These beneficial microorganisms enhance nitrogen fixation and reduce nitrate leaching to minimize nitrogen loss. Concurrently, they suppress N_2O emissions by facilitating complete denitrification to N_2, thereby optimizing soil nitrogen content and supporting sustainable ecosystem functions (Koch and Sessitsch 2024). These data suggest that promoting the use of beneficial microorganisms in soil management is important for improving agricultural productivity and ecological stability.

The stable microenvironment provided by functional materials helps maintain the activity of beneficial microorganisms under various environmental conditions (Xun et al. 2021). Han et al. (2023) found that the addition of biochar to soil resulted in a shift of the dominant species from *Stachybotrys* to *Ascomycetes*, facilitating the accumulation of nutrients in plant shoots to increase final seed yields of wheat and maize by 28% and 35%, respectively. This change in microbial community structure reduced nitrogen loss; biochar application for 3 consecutive years resulted in an average annual increase in soil organic matter of 0.8 g/kg while reducing nitrogen fertilizer requirements (Gao et al. 2024). Additionally, biochar application improves soil water capacity while increasing both the number and activity of soil microorganisms, supporting crop growth under drought conditions (Zhang et al. 2024c).

Ideal microenvironments that meet the oxygen and resource needs of various microbial communities can be created through the design of functional materials with specific spatial structures to optimize microbial survival, growth, and reproduction, improving soil ecological function and health (Rajput et al. 2023). Luo and Luo (2024) found that functional materials with specific pore sizes regulate soil nitrogen cycling through a precise physico-biochemical synergistic mechanism; their multistage pore structure selectively adsorbs ammonium ions and nitrate to achieve slow release of nutrients through surface charge modulation. This pore architecture preferentially supports the colonization and growth of *Azotobacter chroococcum* and *Nitrosomonas europaea*, while macropores induce microanaerobic zones by limiting oxygen diffusion, thereby promoting the expression of *narG* and *nosZ* genes in denitrifying bacteria and enhancing N_2O reduction efficiency under controlled laboratory conditions (Wang et al. 2019b). However, extrapolation of these microscale structural mechanisms to field-scale applications must be approached with caution, as heterogeneous soil structure, variable moisture dynamics, and competing microbial processes in real-world environments may attenuate the observed effects. The modified carboxyl and amino functional groups on the surface of the material form coordination bonds with microbial extracellular polymers to enhance biofilm stability (Sun et al. 2023). This dual mechanism of "physical sieving and chemical bonding" increased soil nitrogen utilization by 30–65% and reduced nitrogen loss by 45–50%, providing a new paradigm for nitrogen management in precision agriculture.

5.3 Reducing competitive pressure

The rational selection and application of functional materials can mitigate competition for labile carbon and nitrogen substrates between exogenous inoculants and indigenous microbial communities, thereby preserving native microbial diversity and reducing nitrogen losses through leaching and gaseous emissions (Wang et al. 2024b). Microenvironments that favor the growth of specific beneficial microorganisms while inhibiting the development of harmful or unwanted microorganisms can be created by regulating material pore structure and surface chemistry (Lin et al. 2023b). Biochar with a pore size of 0.5–5 µm preferentially accommodates nitrogen-fixing and nitrifying bacteria, resulting in a 2.5–fold increase in their colonization density while reducing the abundance of competing microorganisms by 46% (Saravanan et al. 2023). Surfaces can also be made more suitable for the attachment of nitrogen-fixing microbes by adjusting the charge or adding specific ligands. Aminochemical modification of biochar increased the attachment rate of *R. leguminosarum* to 52.6% and increased biofilm biomass by 2.8-fold (Kreve and Dos Reis 2021). Giles et al. (2017) employed ^{15}N labelling techniques to assess sandy loam soil (Dystric Cambisol) collected from Inch, Aberdeenshire, concluding that both the soil material and its microbial community can suppress N_2O emissions and NO_3^- leaching.

Functional materials can also form effective physical barriers to protect native microbial communities from external disturbances. Schommer et al. (2024) demonstrated that the application of biochar with a specific surface area of 580 m^2/g resulted in the adsorption of 62.8% of active soil cadmium along with 92.5% of organochlorine pesticides, significantly reducing their toxicity towards native microorganisms. Clay minerals effectively limit direct contact between exogenous and native microorganisms while preventing the diffusion of exogenous pollutants through electrostatic repulsion, ion exchange, and mechanical blocking, maintaining microbial community stability and diversity (Fomina and Skorochod 2020). Nanomaterials can also be used as carriers to reduce the rate at which harmful substances enter the soil; loaded multi-walled carbon nanotubes reduce the rate of cadmium release, protecting native microorganisms from external pressures (Suresh et al. 2013). Additionally, the use of biodegradable protective films during plant growth has been shown in field studies to suppress soil-borne pathogens by physically impeding their growth and movement toward plant roots (Prasad et al. 2020). Compared to conventional plastic films, these biodegradable alternatives are designed to minimize microplastic persistence, as they undergo complete microbial mineralization in soil, thereby protecting both the crop and the beneficial soil microbial community (Li et al. 2024b). These protective effects ensure the activity of nitrogen-fixing and denitrifying bacteria, maintaining efficient nitrogen cycling while reducing nitrate leaching and N_2O emissions.

By introducing specific enzymes or metabolites into functional materials, the activity of native microorganisms can be stimulated, providing them with a competitive advantage over exogenous microorganisms (Zhu et al. 2024). Additionally, certain functional materials such as biochar and fullerene can improve soil pH, redox potential, and other environmental factors, creating a more favorable environment for native microorganisms and enhancing their competitive ability, helping to maintain efficient nitrogen fixation and denitrification as well as reduce gaseous loss and leaching of nitrogen (Husson 2013). By reducing competitive pressure among microorganisms, functional materials can maintain the diversity and activity of native microbial communities, optimizing key processes of the nitrogen cycle, significantly reducing soil nitrogen loss, and improving nitrogen use efficiency.

5.4 Controlling nutrient release rates

Functional materials, including biochar and organic polymer coatings, can effectively regulate the rate of nutrient release from fertilizers, ensuring a continuous and balanced supply of nitrogen throughout the growth cycle (Zhu et al. 2024). By combining biochar with organic polymer coatings, multiple barriers can be established to enhance physical isolation and allow for precise nutrient management through optimization of nitrogen release while significantly reducing nitrogen loss. Cen et al. (2021) found that biochar-based controlled-release nitrogen fertilizers with a polylactic acid coating significantly extended the nitrogen release time by 32% and reduced the release rate by 46%, optimizing the timing and synchronization of nitrogen application with crop nitrogen demand to increase crop nitrogen uptake by 25.5% and reduce soil nitrogen loss by 32.4%.

The microbial degradation of biodegradable polymers in functional materials, which achieves 93% efficiency under conditions of 25 °C and 60% water content, enhances nitrogen use efficiency by controlling nutrient release (Shen et al. 2013). Nevertheless, the labile carbon released can also stimulate denitrification under high soil moisture, potentially increasing nitrogen gas emissions (Bortoletto et al. 2020). When biodegradable functional materials such as polylactic acid and polyhydroxy fatty acid esters are introduced into the soil, they initially bind to soil particles through physical adsorption or chemical bonding (Fan et al. 2018). Over time, the surfaces of these materials become influenced by microbially secreted enzymes that specifically cleave the chemical bonds within the polymer chains, initiating gradual decomposition (Guo et al. 2024). This microbial-mediated nutrient release mechanism establishes a dynamic equilibrium that provides plants with the nitrogen they need while mitigating soil contamination and nitrogen loss caused by excessive fertilization (Zhang et al. 2020).

Functional management strategies incorporating nanomaterials have shown significant potential in fertilizer applications. The use of nanosilicon as a soil amendment significantly enhances microbial activity and colonization, facilitating effective nutrient conversion (Etesami 2024); additionally, its application with nitrogen fertilizer significantly improved wheat growth, resulting in a 35% increase in nitrogen utilization compared to nitrogen fertilizer alone, underscoring the potential of nanomaterials to enhance nitrogen fertilizer effectiveness (Tayade et al. 2022). Functional materials provide an innovative approach to precisely managing soil nutrients and ensuring a continuous supply of nitrogen by regulating fertilizer release through physical isolation and achieving dynamic nutrient balances through interactions with soil microorganisms (Priya et al. 2024).

5.5 Microbial mitigation

Microbial aggregates mitigate the toxicity of functional materials in soil and regulate nitrogen loss by breaking down harmful components such as heavy metals and organic pollutants, optimizing key nitrogen cycle processes (Zhao et al. 2024c). A biosafety-approved *P. aeruginosa* mutant, by synthesizing 5–10 nm CdS nanoparticles, reduced bioavailable cadmium by 72.4%. This maintained 86.3% of *nifH* expression (82.7% N-fixation recovery, acetylene reduction assay) and increased *amoA* abundance 1.8-fold (47.5% higher nitrification, ^{15}N assay), while reducing N_2O flux by 41.6% (GC) and NO_3^- leaching by 31.2% (^{15}N tracing) (Koul et al. 2021). *Pseudomonas putida* and *Bacillus subtilis* convert highly toxic hexavalent chromium to low-toxicity trivalent chromium, reducing the toxicity of chromium by about 80% and significantly reducing its bioavailability (Ramli et al. 2023). This transformation reduces the inhibitory effect of heavy metals on denitrifying bacteria, facilitating the reduction of nitrate to nitrogen and reducing nitrate leaching and N_2O emissions (Wang et al. 2020a). Microbial aggregates, particularly communities such as *Comamonas testosteroni* and *Pseudomonas* sp., effectively degrade organic pollutants such as polycyclic aromatic hydrocarbons and pesticide residues, playing a crucial role in regulating nitrogen loss; additionally, *P. chrysosporium* rapidly degrades complex organic compounds with lignin–like structures under aerobic conditions (Jiang et al. 2023; Jin et al. 2017). This degradation capacity reduces the toxicity of organic pollutants to nitrogen cycle-associated microorganisms, promoting efficient nitrogen fixation, nitrification, and denitrification (Huang et al. 2011).

Microbial aggregates also adsorb and encapsulate harmful substances, reducing their biological activity and mitigating harmful effects towards plants and soil organisms (Zhang et al. 2024b). EPS are rich in carboxyl, phosphate, amine, and thiol functional groups, enabling them to form organometallic complexes with heavy metal ions. In aqueous batch sorption experiments (pH 6.5, 0.01 M $NaNO_3$), the extracellular polymers produced by *B. subtilis* demonstrated a maximum adsorption capacity of 300 mg/g for lead and cadmium, as quantified by inductively coupled plasma mass spectrometry (ICP-MS), significantly reducing their bioavailability (Marvasi et al. 2010; Pagliaccia et al. 2022). Microbial aggregates also play a crucial role in protecting the activity of microorganisms associated with the nitrogen cycle, increasing the nitrogen fixation efficiency of rhizobia in soils contaminated with heavy metals (Zhang et al. 2022a). By encapsulating heavy metal ions and other toxic substances, microbial aggregates prevent these harmful elements from coming into contact with other organisms (Lu et al. 2022). This not only reduces the risk of pollutant dispersion but also protects the activity of nitrogen cycle–associated microorganisms, maintaining efficient nitrogen fixation and nitrification.

Through synergy with functional materials, microbial aggregates further optimize nitrogen cycling. Functional materials such as biochar and clay minerals reduce the toxicity of heavy metals and organic pollutants by adsorbing them, while providing stable habitats for microorganisms. This synergistic effect significantly reduces soil nitrogen loss. Future research should continue to explore more innovative methods and technologies to further optimize this eco-friendly strategy for both agricultural production and environmental protection.

6 Perspective

In the future, research on mitigating nitrogen loss through the integration of microorganisms and functional materials will explore several avenues and hold significant practical importance. Understanding the synergistic mechanisms between microorganisms and functional materials will lay the groundwork for developing effective nitrogen management strategies. These strategies aim to reduce nitrogen loss and the application of nitrogen fertilizers by enhancing nitrogen adsorption, fixation, and transformation, thereby addressing soil nitrogen pollution. The development of novel and efficient functional materials, such as nanomaterials and natural polymers, will provide essential support for specific microbial communities, subsequently improving nitrogen utilization and enhancing soil health. Such advancements are critical not only for agricultural productivity but also for increasing economic efficiency and reducing environmental pollution. The functional diversity of microorganisms plays a vital role in the nitrogen transformation process. Future research will focus on prioritizing microbial populations capable of efficiently synergizing with functional materials through high-throughput screening techniques, leading to more tailored solutions for agricultural soil improvement. Additionally, genetic engineering and targeted microbial modification are anticipated to further enhance the nitrogen conversion capacity and resilience of microorganisms, thereby strengthening their synergistic effects with functional materials. These technological advancements are expected to propel the field forward, reduce agricultural production costs, and enhance farmland sustainability. By implementing a combination of microbial aggregates and functional materials, agricultural practitioners can effectively mitigate nitrogen pollution, improve soil health, and promote sustainability. These strategies not only address current environmental challenges but also pave the way for future innovations in agricultural technology. With ongoing research and the diffusion of these technologies, microbial–bound functional materials are poised to play an increasingly significant role globally, making substantial contributions to the goals of green agriculture and environmental protection.

7 Conclusion

The integration of microbial aggregates with functional materials represents a highly effective strategy for mitigating nitrogen loss from the environment and addressing the associated environmental pollution issues. This review highlights the progress made in research on microbial aggregates combined with functional materials from various perspectives, identifies the shortcomings of current studies, and outlines key directions for future research. The major strategies identified include: (1) the development of novel functional materials, (2) the screening and characterization of new functional microbial communities, and (3) the application of genetic engineering to enhance microbial nitrogen transformation capabilities. This work not only offers innovative approaches to minimize soil nitrogen loss but also makes a significant contribution to mitigating environmental pollution. Furthermore, these strategies can promote sustainable agricultural practices and contribute to a healthier environment.

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Declarations

Conflict of interests The authors declare no competing interests.

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