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FRONTIERS OF AGRICULTURAL SCIENCE AND ENGINEERING

Engineering Transactions of CAE

REVIEW

2026 / Volume 13 / Issue 1 / 25642

Plastic film mulching and microplastics impact soil nitrogen processes

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KEYWORDS

Plastic film mulching, microplastics, nitrogen fate, nitrogen transformation, arable soil

HIGHLIGHTS

- PFM boosts crop N uptake but raises N_2O emission risk.
- Considerable heterogeneity exists in the N effects observed for microplastics among studies.
- PFM and microplastic impacts on soil N vary with plastic type, environment and crop growth stage.
- Future research should combine long-term experiments with statistical models.

Received March 24, 2025;
Accepted June 3, 2025.

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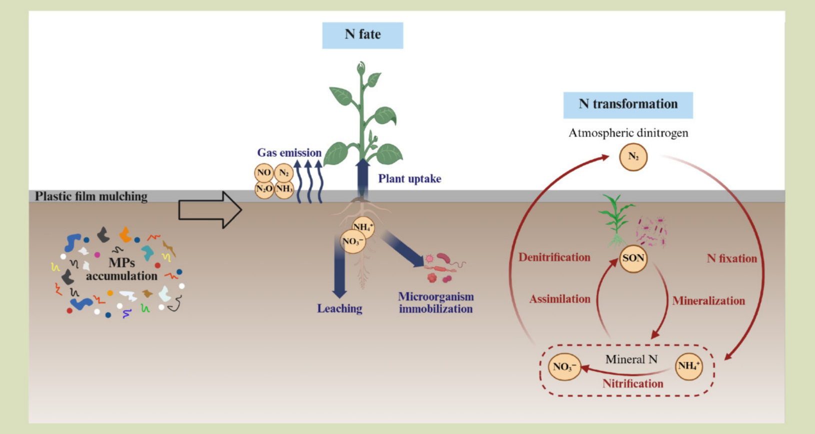
Special Issue: Agricultural Plastic's Application and Problems

GRAPHICAL ABSTRACT



ABSTRACT

Plastic film mulching (PFM) significantly enhances crop yield and quality by increasing soil temperature, reducing water evaporation and optimizing nutrient cycling. However, improper management of plastic film residues has led to microplastic pollution in farmland, posing a major challenge to sustainable agricultural development. The accumulation of microplastics in soil not only affects soil structure but also profoundly impacts crop growth and ecosystem stability by altering nitrogen-related microbial activities and nitrogen (N) cycling processes. This review synthesizes the effects of PFM and microplastics on soil N pools and cycling, exploring their mechanisms in plant N uptake, microbial immobilization, gaseous emissions (e.g., NH_3 and N_2O), and N transformation processes (e.g., N fixation, assimilation, mineralization, nitrification and denitrification). Research indicates that PFM and microplastics significantly influence N processes by modifying soil physicochemical properties and microbial community structure, although their effects vary depending on plastic type, environmental conditions and crop growth stages. Future studies should further investigate the long-term ecological impacts of microplastics in complex natural environments and employ advanced statistical methods and models to quantify their dynamic effects on N cycling.

1 Introduction

Plastic film mulching (PFM), as an important agricultural technology, has been extensively adopted worldwide, particularly in arid and semiarid regions[1]. Specifically, PFM can elevate soil temperature, mitigate water evaporation, optimize soil nutrient cycling and provide a stable environment for crop growth and development. Additionally, it reduces the risk of soil erosion, suppresses soilborne diseases and comprehensively enhances crop yield and quality[2–4]. However, improper management of plastic film residues has become a significant impediment to sustainable agricultural development, including contributing to soil plastic pollution. Plastics in the environment can break down into small plastic particles with a diameter < 5 mm, which are defined as microplastics, while particles with size > 5 mm are referred to as macroplastics[5,6]. The primary sources of microplastics in agricultural fields include PFM, irrigation, coated fertilizers, sewage sludge, organic fertilizer and atmospheric deposition[7]. Of these sources, PFM significantly increases the abundance of microplastics in soil, contributing to 10% to 30% of the total microplastics present in agricultural fields[8]. Given the slow degradation rate of standard plastic films[9], microplastics in farmland soils accumulate progressively with the duration of plastic film use[10]. It should be noted that data on microplastics considered in this review includes results from both field investigation experiments and laboratory-based experiments with artificially added microplastics.

In agricultural ecosystems, the composition and dynamics of soil N pools are crucial for crop growth, soil fertility and ecological stability[11]. The soil N cycle encompasses N pools and transformations. N pools primarily determined by plant uptake, soil retention, microbial immobilization, gaseous emissions (NH_3 and N_2O), runoff and leaching[12]. N transformation involves key processes such as N fixation, mineralization, assimilation, nitrification and denitrification, which together constitute the soil N cycle system[13]. Increasing attention has been directed toward the impacts of PFM and microplastics on soil N processes. However, due to the complexity of soil N cycle and the diversity of plastic films and microplastics, there is considerable heterogeneity among different research findings. For example, Hu et al.[14] found that the presence of microplastics accelerated microbial use of inorganic N, thereby enhancing N fixation and mineralization but inhibiting nitrification and denitrification. Conversely, Su et al.[15] demonstrated that microplastics increased the abundance of denitrification genes and elevated denitrification rates, leading to increased N_2O emissions. This review aims to elucidate the effects of PFM and microplastics on soil N processes, with the goal of identifying new research challenges and directions.

2 Effects of plastic film mulching and microplastics on soil nitrogen processes

N, the most demanded mineral nutrient by plants, is pivotal for promoting plant growth and enhancing crop yield[16]. The presence of PFM and microplastic in soil can significantly influence N processes, including plant uptake, soil N retention, microbial immobilization and gaseous losses (Fig. 1)[17,18].

2.1 Effects of plastic film mulching on soil nitrogen processes

PFM has been demonstrated to enhance crop N uptake and N use efficiency[19,20]. The increased soil water availability under PFM stimulates root growth and improves N use by promoting plant nutrient uptake and aboveground biomass production[20,21]. PFM facilitates N accumulation in the topsoil, significantly increasing total nitrogen content in the 0–20 cm soil layer and organic N content in the 0–30 cm layer[20,22,23]. Also, during crop growth, the N content in the 0–20 cm soil layer under PFM is substantially higher than in bare soil[20].

Soil microorganisms are highly sensitive to changes in their habitat[24]. PFM can stimulate microbial activity by improving soil hydrothermal conditions, thereby accelerating carbon and

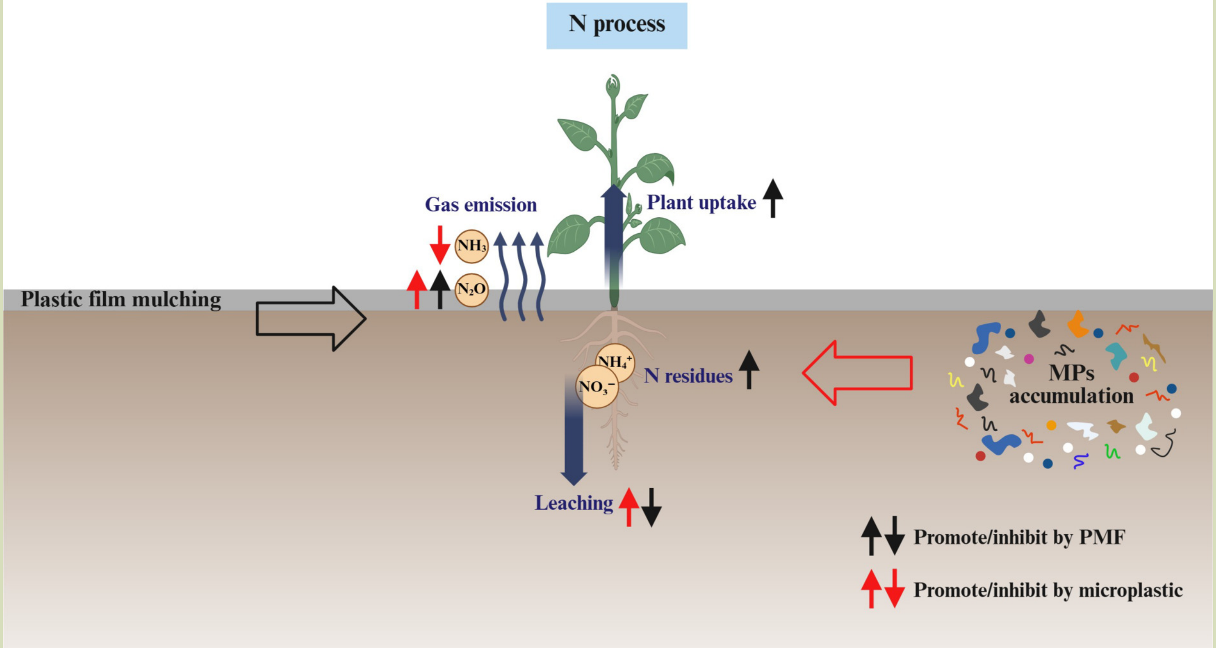


Fig. 1 Effects of plastic film mulching and microplastics on soil nitrogen processes.

N mineralization processes[25,26]. Additionally, PFM affects microbial structure and diversity by increasing nutrient availability, thereby altering the abundance of N-related functional genes associated with microbial N cycling[24,27]. Hossain et al.[20] reported that the average microbial biomass nitrogen content under PFM was 23.6% higher than in bare soil.

PFM increases N loss by stimulating N_2O production and emissions[15], primarily due to elevated soil temperature and moisture, which enhance microbial activity and accelerate organic N mineralization, providing more substrates for nitrification and denitrification[28,29]. Wang et al.[30] found that although N_2O concentration in the 0–20 cm soil layer under PFM was significantly higher than that in bare soil, due to the physical barrier of the plastic film, the total N_2O emissions under PFM decreased by 12%–41%, with biodegradable films exhibiting lower N_2O emissions compared to polyethylene (PE) films. Thus, in the short-term, biodegradable films are considered a viable strategy for maintaining soil quality and reducing N_2O emissions. In addition, during the late stages of crop growth, the fragmentation of biodegradable films results in lower soil temperature, moisture, and mineral N content compared to PE films, leading to reduced microbial activity and N-related enzyme activity (e.g., ammonia monooxygenase). This reduction leads to decreased NO_3^--N accumulation in the topsoil, thereby mitigating negative environmental impacts such as N leaching or gaseous emissions[26].

2.2 Effects of microplastics on soil nitrogen processes

Long-term PFM with inadequate residue management leads to plastic accumulation in soil[31]. Residual plastic films and microplastics alter soil structure and properties, inhibiting the horizontal and vertical distribution of crop roots, disrupting nutrient uptake and even reducing crop yield[22,32]. Fu et al.[22] exposed rice plants to residual plastic film environments and observed suppressed N metabolism pathways and significantly reduced net photosynthetic rates. Liu et al.[33] found that adding 1% polypropylene and 1% rubber particles to soil damaged peanut root cells, inhibited N uptake, and significantly reduced aboveground and underground biomass. In addition, microplastics from biodegradable films, which contain 10% polylactic acid (PLA), 85% polybutylene adipate terephthalate (PBAT) and 5% calcium, have a stronger impact on soil dissolved organic nitrogen and available N (NH_4^+-N and NO_3^--N) compared to standard low-density polyethylene plastic films[34], as biodegradable plastics decompose faster in soil, providing additional carbon sources for N-related microorganisms and promoting the decomposition and transformation of organic N[35]. Also, high concentrations of PE microplastics can adsorb more cations, potentially reducing NH_4^+ availability and decreasing total nitrification and microbial N immobilization rates[34,36]. Overall, residual plastic films can directly or indirectly affect the soil-rhizosphere-microbe-plant system, with microplastics generally considered to have more adverse effects than larger plastic residues[22].

NH_3 and N_2O emissions represent critical manifestations of soil N loss activity. N_2O is produced through nitrification and denitrification processes, closely related to soil NH_4^+-N and NO_3^--N concentrations[37]. One precent PE microplastics increased N_2O emissions by 3.7 times in paddy soils, likely due to the increased abundance of the nitrite reductase gene *nirS*[38]. Conversely, Han et al.[39] found that 10 and 200 μm polyethylene terephthalate microplastics reduced soil NH_3 volatilization due to their strong adsorption capacity for NH_4^+-N. Feng et al.[40] also reported that 0.5% PE and polyacrylonitrile microplastics in paddy soils reduced cumulative NH_3 volatilization by 40% and 57%, respectively. The acidic functional groups (C≡N, C–O and C–OH) and larger surface area, pore volume and pore size of polyacrylonitrile enhance its NH_4^+ adsorption capacity.

Additionally, microplastics can influence N leaching by altering soil aggregates, porosity, and water-holding capacity[41]. Lozano et al.[42] found that microplastics in the shapes of fibers (polyester, polyamide and polypropylene), films (low-density polyethylene, polyethylene terephthalate and polypropylene), foams (polyurethane, PE, polystyrene), and fragments (polyethylene terephthalate, polypropylene, polycarbonate) all reduce the stability of soil aggregates by 9.7%–32.0%. In addition, microplastics may inhibit soil microbial activity, reducing N immobilization and leading to more soluble N in the soil solution, thereby exacerbating N loss[34,36].

In summary, PFM enhances plant N uptake and N accumulation in soil, but it also increases the potential of N_2O emission. Microplastics can inhibit crop N metabolism and photosynthetic rates, while they also affect soil N availability and exacerbating N leaching losses.

3 Effects of plastic film mulching and microplastics on soil nitrogen cycling

N cycling is a crucial part of biogeochemical cycles, especially as a central process in terrestrial ecosystems, making a key contribution to ecosystem stability and productivity[43,44]. In agricultural soils, N cycling includes transformations such as N fixation, mineralization, microbial immobilization, nitrification and denitrification, all driven by microbial and enzymatic activities[45,46]. PFM and microplastic residues can influence soil N transformation processes by altering soil physicochemical properties, thereby affecting microbial abundance and diversity, and enzyme activity (Fig. 2)[47,48]. Additionally, microplastics can adsorb organic and inorganic nutrients, providing a stable habitat for N-related microorganisms and altering microbial community structure and diversity[49]. PFM and microplastics can also influence N cycling by promoting the production of root exudates[50], which include natural biological nitrification inhibitors, including sorgoleone from sorghum[51], brachialactone from *Brachiaria humidicola*[52] and 1,9-decanediol from rice[53]. These compounds can effectively inhibit the activity of ammonia monooxygenase and hydroxylamine oxidoreductase.

3.1 Effects of plastic film mulching on soil nitrogen cycling

Numerous studies have shown that standard PE PFM accelerates soil N transformation processes due to improved soil hydrothermal conditions and enhanced microbial activity[54]. Zhang et al.[24] demonstrated that standard PFM increased the abundance of genes associated with denitrification, anaerobic ammonium oxidation, N fixation, and dissimilatory nitrate reduction to ammonium, whereas biodegradable PFM reduced the abundance of these N-related functional genes.

Zhang et al.[55] found that PFM increased soil temperature and moisture during the peanut growing season, leading to higher total N mineralization and mineral N content, while reducing mineral N leaching. However, the degradation of PLA/PBAT-based biodegradable films decreased soil moisture during the later stages of crop growth, resulting in lower N mineralization rates compared to PE PFM[19,56]. Sun et al.[57] reported that PFM increased the abundance of N-related functional genes such as *pmoB-amoB*, *hao*, *nirB* and *nirD* during the vegetative

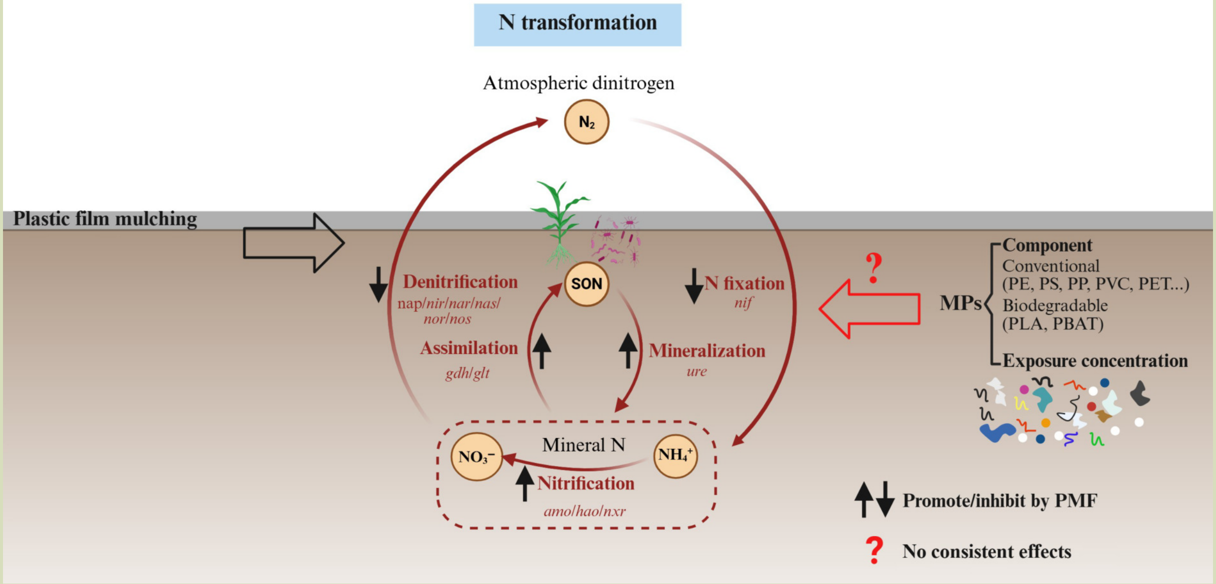


Fig. 2 Effects of plastic film mulching and microplastics on soil nitrogen transformation.

growth stage of maize, promoting nitrification and dissimilatory nitrate reduction to ammonium, thereby increasing rhizospheric inorganic N content. Conversely, during the reproductive growth stage, PFM reduced the relative abundance of aerobic bacteria (e.g., *Skermanella* and *Sphingomonas*) and the ratio of the nitrite reductase genes *nirK* and *nirS* genes to the nitrous oxide reductase gene *nosZ*, inhibiting denitrification and N_2O emission potential. In contrast, black PFM increased N_2O emissions by 21% to 26% due to elevated soil temperature, moisture and CO_2 concentration, as well as enhanced abundance of the nitrification-related functional gene *amoA-AOB*[58]. Both standard and biodegradable plastic films, along with their derived microplastics, collectively influence soil N processes. Guo et al.[59] found that both types of PFM increased soil microplastic abundance and reduced dinitrogenase activity during the peanut seedling stage, ultimately decreasing the proportion of N fixation by root nodules by 54.3%–58.7%.

The effects of PFM on nitrogen transformation also exhibit heterogeneity, driven by variations in local soil properties. For example, while autotrophic nitrification typically dominates soil nitrification processes, the opposite pattern was observed in the acidic soils (pH = 6.1) of Shandong under long-term plastic film mulching, where heterotrophic nitrification became predominant[32].

3.2 Effects of microplastics on soil nitrogen cycling

Microplastics in the environment can provide new attachment sites for microorganisms. Zhang et al.[60] showed that 0.1% PE microplastics enriched bacterial taxa involved in nitrate reduction, nitrate respiration, nitrite respiration and nitrate ammonification, whereas 1% polylactic acid (PLA) microplastics enriched N-fixing bacteria. Microplastics also alter soil physicochemical properties, affecting bacterial community diversity and richness. For example, high doses of PE and polystyrene particles can decrease soil pH, whereas PLA and polyhydroxybutyrate can increase soil pH[61,62]. Additionally, carbon compounds released during microplastic decomposition serve as additional energy and nutrient sources for microorganisms, stimulating their growth and activity[63]. This energy support enhances the expression of the *gdhA* gene in bacterial cells, increasing the activity of enzymes involved in ammonia assimilation (e.g., glutamate dehydrogenase) and ultimately accelerating ammonia assimilation rates[64,65].

Meta-analysis results indicate that microplastic alters the abundance of N-related functional genes, significantly increasing the abundance of genes associated with ammonium assimilation (*gdhA*, effect size = 0.362), N fixation (*nifH*, effect size = 0.191) and urea hydrolysis (*ureC*, effect size = 0.310), while decreasing the abundance of nitrification-related genes (*amoA*, effect size = 0.175)[13]. N fixation is mediated by nitrogenase encoded by the *nif* gene family, which convert atmospheric N_2 into bioavailable N[59,66]. The high C to N ratio of microplastics drives microorganisms to utilize ammonium as a N source for growth, enhancing N fixation and mineralization while suppressing nitrification and denitrification, particularly in the plastisphere[14,67]. Microplastics may directly interact with urease, altering its structure and enhancing its activity, thereby promoting the expression and copy number of the *ureC* gene[13,68]. In addition, microplastics can induce shifts in soil bacterial community structure, favoring the proliferation of urea-degrading bacteria, which increases *ureC* gene copy numbers and urea hydrolysis rates[61].

Nitrification involves multiple proteins, such as ammonia monooxygenase encoded by *amoA*, *amoB* and *amoC* genes, hydroxylamine oxidoreductase encoded by *hao*, and nitrite oxidoreductase encoded by *nxrAB*[69,70]. Microplastics can interfere with bacterial growth through chemical and toxic effects, inhibiting the physiologic functions and gene expression of ammonia-oxidizing microorganisms[71,72]. Some microplastics release acids during decomposition, lowering environmental pH and altering oxygen levels, indirectly impairing the growth and activity of nitrifying bacteria[13].

In denitrification, nitrate is ultimately reduced to N_2, furthering the N cycle. This process involves multiple functional genes, including nitrate reductase genes (*narG*, *narH*, *narI* and *napA*), *nirS* and *nirK*, nitric oxide reductase genes (*norB* and *norC*), and *nosZ*[13]. Su et al.[15] found that microplastics increased the total number of denitrification genes by 10.6%, enhanced nitrate reductase activity by 4.8%, and increased denitrification rates by 17.8%, ultimately raising soil N_2O emissions by over 140%, with these changes predominantly occurring during the early stages of exposure.

Overall, PFM enhances most N transformation processes due to improved soil hydrothermal conditions, but it inhibits nitrogenase activity and enhance denitrification rates during the reproductive growth stage. While microplastics influence N cycling by altering N-relate microorganisms structure and functional genes abundance, though the effects exhibit significant heterogeneity across studies due to variations in microplastic composition and concentration.

4 Perspectives

Given the uncontrollable and complex nature of natural environmental conditions, studies conducted in laboratory settings with precisely controlled variables cannot fully replicate the complexity and dynamic changes of N cycling in natural environments[31]. Therefore, future research should first expand experimental investigations to account for the influence of complex environmental variables, such as soil properties and climate change, although this may increase the uncertainty in assessing the impact of PFM and microplastics on N cycling. In addition, a more comprehensive and systematic approach should be adopted in subsequent studies to delve deeper into the effects of microplastics on soil N cycling. This includes: (1) extending the time scale of experimental monitoring to track microplastic degradation processes and their environmental effects, thereby revealing their dynamic impacts on key N cycling processes; and (2) broadening evaluation metrics to encompass bacterial community structure, functional diversity and gene expression levels, enabling deeper insights into the ecological consequences of microplastics. Finally, multidisciplinary approaches should be adopted by integrating advanced statistical models and experimental findings to accurately quantify the interactions between soil-climate factors and microplastics in N cycling under natural environmental conditions in order to realize the green eco-environment target[73].

5 Conclusions

The impacts of PFM and microplastics on soil N processes are complex and diverse. PFM improves soil hydrothermal conditions, promoting crop N uptake and microbial activity, but also increases the risk of N_2O emissions. The accumulation of microplastics significantly affects N transformation processes by altering soil structure, microbial communities and enzyme activity, although the heterogeneity among different studies is more pronounced. While some laboratory studies have revealed potential mechanisms of microplastics on N cycling, their long-term effects in natural environments require further investigation. Future research should adopt multidisciplinary approaches, extend observation time scales and comprehensively consider complex factors such as soil properties and climate change to fully assess the ecological risks of PFM and microplastics on agricultural ecosystems. This will provide scientific support for developing sustainable farmland management strategies.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (42277097), Ordos Science and Technology Major Project, China (ZD20232320), the High-level Talent Program of Hebei Province, China (2024HBQZYCXY037), Professor Station of China Agricultural University at Xinzhou Center for Disease Control and Prevention, and the National Key R&D Program of China (2023YFD1900604).

Compliance with ethics guidelines

Jinrui Zhang, Kai Wang, Tong Zhu, Tao Cheng, Rui Jiang, and Xuejun Liu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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