ADVANCES AND POTENTIALAPPLICATIONS OF BIOCHAR-BASED ORGANOMINERAL FERTILIZERS TO IMPROVE NITROGEN USE EFFICIENCY

Allana Kedry Mattos Marques [1], Dirlane de Fátima do Carmo [1], Mariana Vezzone [1], David Vilas Boas de Campos [2]

[1] FLUMINENSE FEDERAL UNIVERSITY, BRASIL
[2] EMBRAPA SOILS, BRASIL

Abstract

Nitrogen (N) is an essential nutrient for plant growth, but its use efficiency (UNE) is often limited by losses due to leaching, NH volatilization, and denitrification, impacting both productivity and the environment. Factors such as fertilizer type, soil characteristics, climate, and crop directly influence UUE, with sandy tropical soils being particularly susceptible to N losses. Biochar derived from organic waste has proven effective in mitigating these losses, acting as a soil conditioner, increasing pH, moisture retention, porosity, and microbial activity, favoring greater N absorption by plants. This review summarizes recent evidence on the role of biochar in improving ENU, reducing N losses, and enabling innovative fertilizer formulations. Studies indicate that biochar modified or used as a coating for urea, as well as organomineral fertilizers, promotes the gradual release of N, increases macroaggregate stability, reduces leaching and gaseous emissions, and increases productivity. In addition, innovative formulations incorporating lauric acid or *Hermetia illucens* by-products increase the multifunctionality of biofertilizers and contribute to circular economy practices. These strategies link nutrient management to waste valorization, contributing to more sustainable fertilization approaches.

Keywords: sustainability, organic waste, black fy soldier, nitrogen oss, circular economy

INTRODUCTION

Nitrogen (N) is one of the most important nutrients for plant growth and development and is often applied in agricultural systems in the form of chemical fertilizers. However, nitrogen use efficiency (NUE) is often limited by losses through ammonia (NH_3) volatilization, nitrate (NO_3-) leaching, and denitrification, which compromise nutrient availability and increase environmental impacts. Factors such as fertilizer type, soil characteristics, climate, and crop directly influence NUE. For example, Abbruzzini et al. (2019) reported that sandy tropical soils have low N retention capacity, high acidity, and significant N loss through denitrification. The application of biochar can partially mitigate these losses by increasing soil pH, moisture retention, and porosity, thus promoting greater N absorption and increased productivity.

The physicochemical properties of biochar vary according to the organic raw material and production conditions, which means that biochar derived from different organic wastes has different capacities to influence soil processes. These differences directly affect N dynamics, altering the retention of inorganic forms such as ammonium (NH_4+) and NO_3-, as well as stimulating microbial activity and increasing soil pH, factors that regulate mineralization and nitrification (Priya et al., 2024; Yu et al., 2024). Trials combining biochar with nitrogen fertilizers show greater N retention, reduced losses through leaching and volatilization, and gradual nutrient release more in line with crop cycle needs (Jaffar et al., 2025).

This literature review aimed to synthesize and critically analyze peer-reviewed studies published between 2020 and 2025, focusing on:

(i) NUE in systems corrected with biochar; (ii) N losses through leaching, NH3 volatilization, and denitrification; and (iii) the potential of innovative formulations, including biochar-coated urea, organomineral fertilizers, and lauric acid as a potential nitrification inhibitor.

MATERIALS AND METHODS

A systematic review of the literature in indexed scientific journals (e.g., Biochar, Journal of Environmental Management, Science of the Total Environment, Soil & Tillage Research, Sustainability) was conducted using the Periódicos Capes platform. Articles published between 2020 and 2025, available in full and peer-reviewed, were included. The selected studies were organized into four main thematic groups: NUE, leaching, volatilization, and denitrification. Keywords were strategically combined to ensure consistency with the study objectives. For the NUE group, the following keywords were listed: nitrogen use efficiency and biochar and field experiment, finding 169 initial articles. For the leaching group: nitrate leaching and biochar, finding 227 initial articles. For the volatilization group: nitrogen volatilization and biochar, finding 184 initial articles. For the denitrification group: denitrification and biochar, finding 394 initial articles.

Table 1 summarizes the keyword combinations used as a search strategy to select articles from the knowledge base. Terms in English and Portuguese were used, connected by Boolean operators (AND, OR), in order to increase sensitivity and precision in retrieving relevant articles. Articles were selected using the following exclusion criteria: duplicates, absence of results in the field or greenhouses, absence of focus on biochar and nitrogen, and limited to publications between 2020 and 2025.

Table 1. Search strategy and keyword combinations used to identify peer-reviewed articles published between 2020 and 2025 on nitrogen use efficiency (NUE), nitrogen losses, and innovative fertilizer formulations.

Thematic Block	Number of articles found	Examples of crops/soils	Main findings
NUE	98	Corn, vegetables, rice	↑ N uptable, ↑ yield, ↓ residual N
Leaching	62	Field/ soil column	↓NO_3^- losses whit biochar-urea
Volatilization	52	field/vegetables	Partial reduction, depends on biochar pH
Desnitrification	178	field/greenhouse	↓ N_2O, ↑ conversion to N_2

Source: Prepared by the authors.

The thematic blocks were defined based on the main pathways of nitrogen loss (leaching, volatilization, and denitrification) and NUE, with complementary axes focused on slow-release fertilizers, organomineral fertilizers, urea coated with biochar, lauric acid, and bioconversion of waste with *Hermetia illucens*. This approach made it possible to map the most recent studies (2020-2025) published in internationally relevant indexed journals, covering both field and greenhouse studies. The standardization of combinations ensures reproducibility and transparency in the literature review, as well as helping to identify gaps and trends in research.

RESULTS AND DISCUSSION

Biochar impacts on Nitrogen Use Efficiency (NUE)

The application of biochar has been consistently associated with improvements in NUE in different cropping systems. In a two-year study in an intensive rice-wheat system, Wang et al. (2019) reported that biochar application reduced N O emissions by up to 38.7%
2

compared to the control treatment, without compromising productivity. This effect was attributed to increased N retention in the soil and changes in the microbial dynamics of denitrification. Similarly, Zhou et al. (2021), working on open-field vegetable systems, found that the use of biochar-based organomineral fertilizers improved NUE by 15.6% when compared to the use of conventional urea. Structural modification of biochar can increase its effects, and Khan et al. (2023) showed that modified biochar increased the formation of water-stable macroaggregates, favoring N retention and reducing gaseous emissions.

The positive effects of biochar on NUE are largely attributed to its ability to alter the physical and chemical conditions of the soil. Modified biochars, for example, have been shown to increase the formation of stable macroaggregates in water, improving soil structure and physically protecting nitrogen from loss (Khan, 2023). Broader evidence also highlights that biochar additions can increase soil pH and organic carbon while stimulating microbial activity, thus creating conditions that favor nitrogen mineralization and its uptake by plants (Yu et al., 2024; Feng et al., 2021).

Nitrogen losses

Biochar additions play a key role in mitigating the main pathways of N loss, although results vary depending on soil type, formulation, and management. In open-field vegetable systems, the application of biochar-based fertilizers reduced nitrate leaching by 18.4% and NH volatilization by 22.7% compared to conventional urea (Zhou et al., 2021). These effects were attributed to improved retention of ammonium (NH) and nitrate (NO) in soil aggregates, thereby limiting nutrient mobility. Supporting this, Kumar et al. (2025), in a comprehensive review, emphasized that biochar with high surface area is particularly effective in adsorbing nitrate, especially in sandy soils where the risk of leaching is higher.

Losses due to denitrification can also be reduced through the application of biochar. In intensive rice and wheat rotations, biochar reduced N_2O emissions by up to 38.7% compared to untreated plots (Wang et al., 2019), while Pereira et al. (2022) demonstrated that organomineral fertilizers enriched with activated biochar slowed nitrogen release and reduced N2O fluxes. These findings indicate that biochar not only slows nutrient loss but also influences microbial processes related to the nitrogen cycle.

However, disadvantages were also observed. In some cases, NH_3 volatilization increased after the addition of biochar, probably due to its alkalizing effect (Zhou et al., 2021). This negative result, however, was partially offset by increased plant uptake, suggesting that the net impact on nitrogen availability may still be positive.

Innovative Formulations

Recent advances highlight the potential to expand the applications of biochar for innovative fertilizer formulations, connecting agricultural efficiency and the circular economy. One promising strategy involves the development of slow-release fertilizers. Wang et al. (2022) reviewed advances in the production of biochar as a matrix for fertilizer coating, highlighting methods such as pyrolysis, impregnation, and encapsulation, which make it possible to reduce the rate of N dissolution and, consequently, losses. Similarly, Jia et al. (2020) found that biochar derived from sugarcane bagasse, prepared at 600 °C, had greater adhesion to urea and better control of N release, proving to be suitable for the formulation of biochar-coated urea. Similarly, Magalhães et al. (2022) showed that biochar-coated urea can delay N release and reduce losses.

Organomineral fertilizers represent another avenue for innovation. Pereira et al. (2022) showed that adding activated biochar to organomineral fertilizers slowed N release and reduced N O emissions in agricultural systems. Fachini et al. (2021) characterized a K-enriched organomineral fertilizer from pyrolyzed sewage $_2$sludge, obtaining up to a 75-fold increase in K O content compared to pure biochar, which expands the multifunctionality of this type of input. These findings expand the multifunctionality of organomineral fertilizers, combining N stabilization with the supply of additional nutrients.

Pan et al. (2024), in a meta-analysis of 144 studies, found that nitrification inhibitors and polymer-coated urea increased plant productivity by 7.5-8.1%, reduced NO leaching by 45.8%, and N O emissions by 40.5%, although inhibitors increased NH volatilization by 32.4%.

In addition to conventional formulations, other studies have explored the incorporation of lauric acid and insect-derived by-products. Srivastava et al. (2023) tested lauric acid as a component of controlled-release fertilizers, while Leong et al. (2021) explored *Hermetia illucens* oil as a source of lauric acid. These studies emphasize the need for further work combining biochar with lauric acid, with a view to better exploiting the product for slow-release technology, transforming organic waste into value-added fertilizers.

Although studies on lauric acid and *Hermetia illucens* demonstrate potential as alternative sources of compounds for controlled-release fertilizers, there is no evidence of interaction between these resources and biochar. Studies such as Srivastava et al. (2023) address lauric acid in microalgae, and Leong et al. (2020) and Santos (2021) investigate the production of lauric oil via *H. illucens*, but without association with biochar. Thus, such approaches should be presented as prospective innovation and not as findings from the systematic review.

FNAL CONSIDERATIONS

This review demonstrated that biochar, when applied with other nutrient sources, can improve NUE and mitigate losses through leaching, volatilization, and denitrification, reducing greenhouse gas emissions. Evidence from recent studies confirms its multifunctional role as a soil conditioner and nutrient carrier, contributing to improved N availability during periods of high crop demand.

Innovative formulations, such as biochar-coated urea, organomineral fertilizers, and biofertilizers with lauric acid, expand the potential applications of biochar and can contribute to the development of sustainable agriculture. Furthermore, the incorporation of organic waste and insect by-products reinforces the role of circular technologies in sustainable fertilization, offering strategies to reduce the environmental impacts of mineral fertilizers applied to the soil.

The integration of biochar, urea, and controlled release technologies is an innovative strategy to reduce environmental impacts and increase nitrogen use efficiency in tropical agricultural systems. Despite these advances, many studies are still exploratory or laboratory-based, with few long-term field trials. Therefore, more long-term field studies with biochar from different raw materials are still needed to validate its large-scale applicability.

REFERENCES

Abbruzzini, Thalita Fernanda; Davies, Christian Andrew; Toledo, Fernando Henrique; Cerri, Carlos Eduardo Pellegrino. **Dynamic biochar effects on nitrogen use efficiency, crop yield and soil nitrous oxide emissions during a tropical wheat-growing season.** Journal of Environmental Management, v. 252, p. 109638, 2019.

FACHINI, Jóisman; FIGUEIREDO, Cícero Célio de. **Novo fertilizante à base de biochar de lodo de esgoto enriquecido com potássio: caracterização, liberação de K e potencial agronômico.** 2022. Tese (Doutorado em Agronomia) — Universidade de Brasília, Brasília, 2022.

FENG, Weiying; YANG, Fang; CEN, Rui; LIU, Jing; QU, Zhongyi; MIAO, Qingfeng; CHEN, Haiyan. **Effects of straw biochar application on soil temperature, available nitrogen and growth of corn.** Journal of Environmental Management, v. 277, p. 111331, 2021. DOI: 10.1016/J.JENVMAN.2020.111331.

JAFFAR, Muhammad Tauseef; CHANG, Wenqian; AHMED, Muhammad; SHI, Ruoxuan; LIU, Qingzhu; GIRKIN, Nicholas; CAO, Yi; JIANG, Wei; LI, Xiong; ZHANG, Jianguo. Mechanistic insights into the role of biochar C:N ratios in modulating greenhouse gas emissions and soil organic carbon fractions in contrasting soil types. **Soil Science Society of America Journal**, v. 89, e70068, 2025. DOI: 10.1002/saj2.70068.

JIA, Yiman; HU, Zhengyi; MU, Jing; ZHANG, Wantong; XIE, Zijian; WANG, Guoxi. Preparation of biochar as a coating material for biochar-coated urea. **Science of The Total Environment**, v. 731, p. 139063, 2020. DOI: 10.1016/j.scitotenv.2020.139063.

KHAN, Zaid; YANG, Xu-Jian; FU, Youqiang; JOSEPH, Stephen; KHAN, Mohammad Nauman; KHAN, Muhammad Ayoub; ALAM, Intikhab; SHEN, Hong. Engineered biochar improves nitrogen use efficiency via stabilizing soil water-stable macroaggregates and enhancing nitrogen transformation. **Biochar**, v. 5, n. 1, p. 52, 2023. DOI: 10.1007/s42773-023-00252-8.

KUMAR, Rakesh; RAHMAN, Atiqur; LAMBA, Jasmeet; ADHIKARI, Sushil; TORBERT, Henry Allen. Harnessing biochar for nitrate removal from contaminated soil and water environments: economic implications, practical feasibility, and future perspectives. **Biochar**, v. 7, p. 94, 2025. DOI: 10.1007/s42773-025-00486-8.

YOONG, Leong Siew; KUTTY, S.R.M.; MALAKAHMAD, Amirhossein. Feasibility study of biodiesel production using lipids of ***Hermetia illucens*** larva fed with organic waste. **Waste Management**, v. 47, part A, p. 187–193, 2015. DOI: 10.1016/j.wasman.2015.03.030.

MAGALHÃES, Ciro Augusto de Souza; SANTOS, Bruna Larissa da Silva dos; PETTER, Fabiano André; MATOS, Eduardo da Silva; FURTINI, Isabela Volpi; MORALES, Marina Moura. The use of biochar-urea pellet formulations to reduce nitrogen losses. **Journal of Environmental Management**, v. 325, p. 116505, 2023. DOI: 10.1016/j.jenvman.2022.116505

PAN, Zhaolong; HE, Ping; FAN, Daijia; JIANG, Rong; SONG, Daping; SONG, Lei; ZHOU, Wei; HE, Wentian. Global impact of enhanced-efficiency fertilizers on vegetable productivity and reactive nitrogen losses. **Science of The Total Environment**, v. 926, p. 172016, 2024. DOI: 10.1016/j.scitotenv.2024.172016.

PEREIRA, Valéria Viana; MORALES, Marina Moura; PEREIRA, Dalton Henrique; MAGALHÃES, Ciro Augusto de Souza; REZENDE, Fabiana Abreu de; LIMA, Larissa Borges de; MARIMON-JUNIOR, Ben Hur; PETTER, Fabiano André. Activated Biochar-Based Organomineral Fertilizer Delays Nitrogen Release and Reduces N2O Emission. **Sustainability**, v. 14, n. 3, p. 1567, 2022. DOI: 10.3390/su14031567.

PRIYA, E.; SARKAR, Sudipta; MAJI, Pradip K. A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. **Journal of Environmental Chemical Engineering**, v. 12, p. 113211, 2024. DOI: 10.1016/j.jece.2024.113211.

SRIVASTAVA, Kautilya; MICKAN, Bede S.; O’CONNOR, James; GURUNG, Sun Kumar; MOHEMANI, Navid R.; JENKINS, Sasha N. Development of a controlled release fertilizer by incorporating lauric acid into microalgal biomass: Dynamics on soil biological processes for efficient utilisation of waste resources. ***Journal of Environmental Management***, v. 344, p. 118392, 2023. DOI: 10.1016/j.jenvman.2023.118392.

WANG, Chongqing; LUO, Dan; ZHANG, Xue; HUANG, Rong; CAO, Yijun; LIU, Gonggang; ZHANG, Yingshuang; WANG, Hui. Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review. **Environmental Science and Ecotechnology**, v. 10, p. 100167, 2022. DOI: 10.1016/j.ese.2022.100167.

WANG, Shuwei; MA, Shutan; SHAN, Jun; XIA, Yongqiu; LIN, Jinghui; YAN, Xiaoyuan. A 2-year study on the effect of biochar on methane and nitrous oxide emissions in an intensive rice–wheat cropping system. **Biochar**, v. 1, n. 2, p. 177–186, 2019. DOI: 10.1007/s42773-019-00011-8.

YU, Binbin; YANG, Keming; CUI, Min; CHEN, Zilong; DAI, Yuanyuan; QIAN, Xiaoqing; CHEN, Zhongzhi. Meta-Analysis Study on the Role of Biochar on Soil Nitrogen Cycling. **Journal of Soil Science and Plant Nutrition**, v. 24, n. 3, p. 312–325, 2024. DOI: 10.1007/s42729-024-00098-7.

ZHOU, Miaorong; YING, Shanshan; CHEN, Junhui; JIANG, Peikun; TENG, Yuanxin. Effects of biochar-based fertilizer on nitrogen use efficiency and nitrogen losses via leaching and ammonia volatilization from an open vegetable field. **Environmental Science and Pollution Research**, v. 28, p. 23456–23467, 2021. DOI: 10.1007/s11356-021-15210-9.