



REVIEW ARTICLE

Influence of biochar on soil nitrogen dynamics: Critical review with bibliometric insights

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Abstract

Excessive application of nitrogenous fertiliser poses a significant threat to environmental sustainability. Biochar has emerged as a multifunctional amendment to mitigate this environmental risk by increasing nitrogen (N) retention and nutrient use efficiency across diverse agro ecosystems. This review critically synthesises evidence from meta-analyses, incubation and field studies to elucidate how biochar influences N transformation and different loss pathways such as denitrification, leaching and volatilisation. The large surface area, porous structure and variable surface chemistry of biochar results in increasing ammonium (NH_4^+) adsorption and reduction in nitrate (NO_3^-) leaching, thereby enhancing N retention in soil, which is governed by several factors, such as application rate, feedstock type, pyrolysis temperature and soil condition. To contextualise this evidence, a bibliometric review of 1026 scopus-indexed articles published between 2017–26 was carried out using bibliometrix with biblioshiny and VOSviewer. The findings indicated a rapid diversified growth of scientific production and a transition from broad subjects, e.g. soil improvement and carbon management to narrower subjects, e.g., N dynamics, microbial communities and soil health. The network analysis also indicated that the field continues to diversify into new application-oriented fields. We identified methodological inconsistencies and proposed validation through long-term studies and site-specific response models for future research.

Keywords: biochar; nitrogen dynamics; research trends; scopus; thematic evolution

Introduction

Biochar, a carbonaceous material produced by pyrolysis of biomass under anaerobic conditions, has emerged as a promising soil amendment in agricultural systems due to its potential to improve soil fertility, enhance carbon (C) sequestration and mitigate environmental nitrogen (N) losses (1). Nitrogen dynamics play a vital role in agricultural soils so far crop productivity as well as environmental sustainability are concerned. The indiscriminate use of nitrogenous fertiliser leads to emission of nitrous oxide (N_2O), ammonia (NH_3) volatilisation and NO_3^- leaching, causing greenhouse gas emissions and water pollution respectively. Biochar influences these processes through different mechanisms, including direct adsorption of inorganic N forms on its porous structure, a greater surface area, abundant surface functional groups, thereby enhancing water and nutrient retention, alteration of soil pH, inhibition of microbial N-cycling communities and changes in mineralisation, nitrification and denitrification rates as reflected in Fig. 1. Recent meta-analyses have highlighted that biochar can

absorb appreciable quantities of NO_3^- mainly through the high-temperature pyrolysis process, while NH_4^+ adsorption and capture of NH_3 varies with nature of feedstock. Application of biochar also decreases volatilisation losses during manure management (2, 3). Biochar often interacts with N inputs to enhance its use efficiency, plant uptake and crop yields while mitigating losses, particularly in sandy or acidic soils by improving nutrient retention (4). In this context, the impacts of biochar include both potential N immobilisation following the application of biochar with a high C : N ratio and short-term increase in N availability from low-temperature biochar. These interactions demonstrate that the use of biochar as a mutually beneficial strategy for sustainable N management, balancing productivity gains with reduced environmental impacts, though long-term studies and mechanistic insights remain essential to optimise its application across diverse agro ecosystems (5).

Because of its ability to enhance the soil quality, increase nutrient retention, support crop productivity and mitigate climate change, biochar has become a potential soil amendment in modern

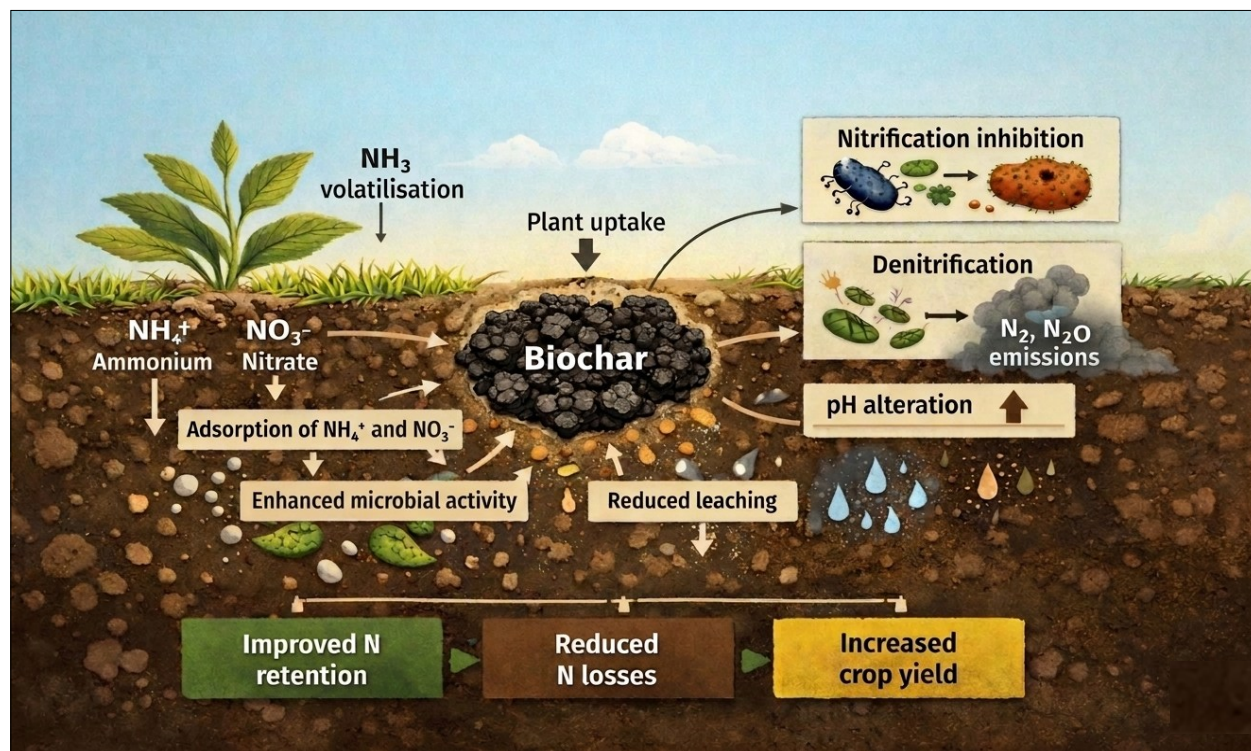


Fig. 1. Influence of biochar on nitrogen transformation in soil.

agricultural and environmental study. Biochar is obtained as a result of the thermochemical transformation of biomass in a limited oxygen environment and has comparatively high C stability, porous structure and surface reactivity, which render it suitable for both agronomic and ecological applications (6, 7). Previous research indicated that biochar is not only a C sequestration tool, but also, a soil conditioner, which is able to enhance physical, chemical and biological characteristics of the soil systems (6). Due to these multifunctional properties, biochar has become increasingly popular as a potential tool for sustainable soil management.

Accumulated evidence has demonstrated that the impacts of biochar on soil are closely linked to the increase in nutrient availability, soil fertility, water retention, buffering capacity, C sequestration and contaminant fixation. Previous reviews have reported that biochar application can stimulate plant growth, enhance crop production and decrease N losses and these effects depend on the nature of the feedstock, conditions of the pyrolysis process, the type of soil and the management scenario (8–10). Additionally, more recent research has emphasised that biochar has a significant role in determining the soil biological health, through both altering the soil microhabitat and promoting microbial diversity as well as changing the biogeochemical processes associated with nutrient cycling and soil resilience (11). These results imply that biochar cannot be considered as a universally homogeneous amendment, but rather a context-specific material whose effects depend on the interactions of the properties of the soil, plant systems and management practices.

Recent experimental studies have demonstrated that biochar, especially in combination with N fertiliser, can enhance soil nutrient content, change the structure of the microbial community in the rhizosphere and lead to increased crop yield in different agricultural systems (12). This increasing focus on the interactions between biochar, accessible N, microbial communities and soil functioning indicates an overall change in the direction of the field from general discourse on soil amendments to more process-based

and more mechanism-based studies. Existing reviews on biochar and soil N tend to emphasise only on its effects on N-dynamics and different N loss pathways while paying less attention to the contradictory findings and methodological heterogeneity. The negative impacts of biochar on N loss such as biochar-induced increased NH₃ volatilisation as reported in some studies are rarely explained. This review article addresses the mentioned gaps by synthesising the recent advances in understanding the role of biochar in soil N dynamics, evaluating contradictory findings and identifying methodological weaknesses across various studies. As the biochar related literature continues to grow rapidly, spanning multiple disciplines, this review systematically presents a bibliometric analysis using Scopus-indexed database to examine publication trends, geographic distribution and thematic evolution of biochar research related to soil N management. This review article is intended to provide a clear picture regarding the present status of biochar-N research and future research directions.

Methodology

The study was based on a bibliometric analysis of the global research landscape regarding the effect of biochar on N dynamics in soil. The bibliographic information was gathered using only the Scopus database and the reason was its wide coverage of peer reviewed publications as well as its applicability to bibliometric and science-mapping research. The search strategy was designed based on the term “biochar”, soil N and available N, following the logic presented in the screening note that was followed when collecting data. Soil N represents the total N in soil including both mineralisable as well as stable N pool, while available N reflects and mineralisable pools of N. The formal form of the search was as follows: (biochar AND soil N) AND (biochar OR available N). The first search in Scopus found 1412 records. A progressive screening process was used to narrow down the dataset and make it relevant and consistent. To begin with, the publication year was limited to 2017–26 which reduced the number of records to 1287. Second, only articles were included and the total number of records was 1202. Third, the

language was limited to the English and resulting in a final dataset of 1026 articles for bibliometric analysis. This final dataset aligns with the bibliometric analysis of the data, which revealed a corpus of 1026 documents that have been published between 2017–26 and 258 sources (Fig. 2).

The final dataset was extracted from Scopus in the form of a complete bibliographic records, namely titles, authors, abstracts, keywords, affiliations, sources, references and citation data. The data were pre-checked and standardised to minimise the discrepancies present in the author names, source titles, affiliation and keywords before the analysis. Keyword harmonisation was also performed where necessary in order to consolidate similar terms and eliminate fragmentation in thematic and network analysis. The filtered data were further processed using the bibliometric package in R through the Biblioshiny interface and bibliometric networks were visualised with VOSviewer. The data were analysed in terms of annual scientific output, citation patterns, source organisation, major affiliations and authorship, the countries of the authors, keyword combinations, thematic change, concept organisation, collaboration and citation networks. The corpus was finally narrowed down to 1026 articles, 5241 authors, 258 sources and 29.04 % of the publications were internationally co-authored, indicating that the field is both active and collaborative.

Methodological weakness

Several methodological shortcomings should be acknowledged. Since the study relied solely on the Scopus database, other databases may have excluded relevant studies indexed in other databases. Citation-based indicators can also be biased towards older articles as they have had more time to accumulate citations. Several studies report only the biochar application rate without complete characterisation and without reporting the pyrolysis temperature, feedstock ash content or surface chemistry, even though these variables are the major determinants of the N response. Apart from this, the experimental duration is very short

with many studies consisting of short-term incubations or field experiments lasting only one or two years of biochar application which creates uncertainty in projecting the N release and retention pattern of soil under biochar application. Regardless of these shortcomings, the chosen dataset offers a sound and stable foundation of the study of the trends in publications, the thematic evolution and the knowledge structure of biochar research in soil amendment.

Properties of biochar relevant to nitrogen dynamics

The properties of biochar can significantly influence N dynamics within soil, including N availability, leaching and cycling. These influences vary with factors such as feedstock type, pyrolysis temperature and soil conditions. Biochar properties such as pH, cation exchange capacity, specific surface area, C stability, porosity, functional groups and nutrient content are predominantly governed by feedstock type and pyrolysis conditions, particularly temperature (13).

Selection of feedstock exhibits the dominant effect, with wood-based materials typically producing biochar with high specific surface area, porosity and C stability, thereby improving physical adsorption and long-term nutrient retention while reducing leaching (14). However, crop residue-based feedstocks generate biochar rich in oxygen, hydrogen and N containing functional groups, high ash content, elevated pH and increased cation exchange capacity, thereby enhancing the chemical adsorption of cations (e.g., NH_4^+ , Ca^{2+}) and increasing short-term N availability (15). Pyrolysis temperature further regulates these traits: lower pyrolysis temperature preserve more volatile matter, acidic functional groups and nutrients, resulting in higher cation exchange capacity and reactivity for anion/cation binding and short-term N supply, while higher pyrolysis temperature enhance aromaticity, specific surface area, porosity, pH and recalcitrance favouring stable physical nutrient sorption and minimising the priming effect on mineralisation of soil organic matter (14).

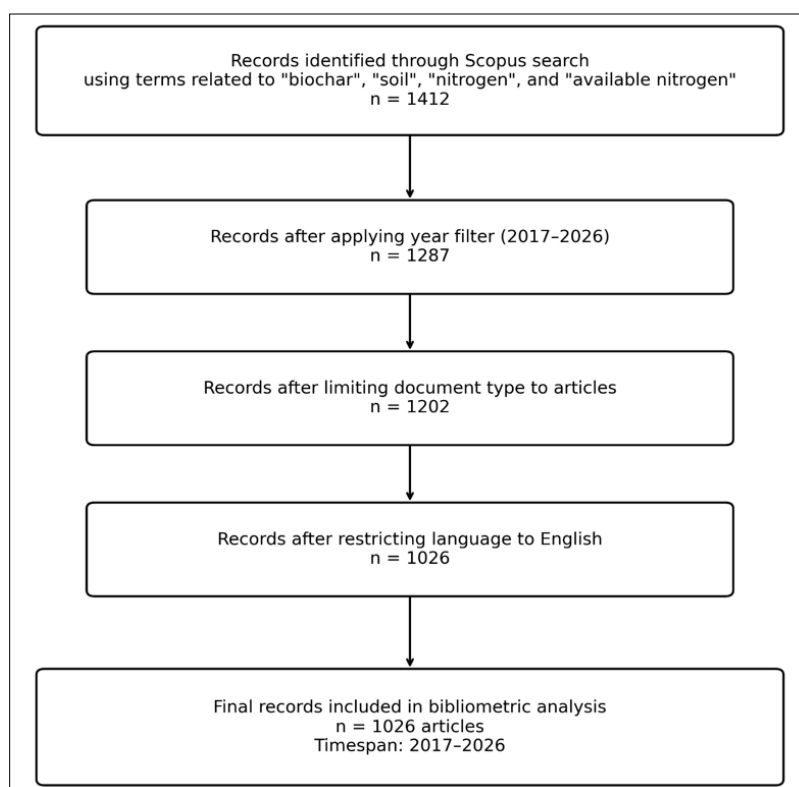


Fig. 2. PRISMA flowchart of study selection.

Soil N stock acts as an essential indicator of crop productivity as well as soil fertility, as it reflects the quantity of N stored in a specific volume of soil that supports crop growth and yield. Biochar derived from different feedstocks significantly influence soil N stock through direct nutrient addition, sorption, microbial transformations and reduced losses. Feedstock composition dictates biochar properties such as total N content, volatile matter (VM), ash, pH, cation exchange capacity (CEC) and C lability, thereby modulating N mineralisation, immobilisation, nitrification, denitrification and leaching (13, 16).

Manure and biosolids-based biochar contains the highest total N content (due to higher proteins and amino acids in feedstocks), directly elevating soil N pools and serving as slow-release sources. These biochars enhance mineralisation in N-rich contexts while improving retention via high ash-derived pH and CEC, reducing $\text{NH}_4^+/\text{NO}_3^-$ leaching and N_2O emissions. Manure-based biochar has been reported to enhance microbial biomass N more effectively than lignocellulosic biochar due to their higher labile nutrient content. Crop residue feedstocks (e.g., maize stover, rice straw, comcob) provide intermediate levels of N with metabolisable aliphatic/phenolic C; they prime microbes to mineralise recalcitrant soil organic N in low-fertility soils (positive for available N stock) but high-volatile matter biochars may cause short-term immobilisation, thereby depleting inorganic N ($\text{NH}_4^+/\text{NO}_3^-$) (17). Woody feedstocks (e.g., eucalyptus, kiawe, pine) produce low-N, highly aromatic biochars that contribute minimally to direct N addition but boost long-term stock via superior porosity and surface area, sorbing NH_4^+ (leaching reductions of 55–94 %). Herbaceous/leguminous types raise pH more effectively than woody ones, favouring nitrification in acidic soils (16). Overall, the manure/crop-based biochar best augments the N stock in infertile soils via addition and stimulation of cycling, while woody types excel in retention. Pyrolysis temperature and soil conditions interact with these effects (13, 18).

Effects of biochar on nitrogen dynamics

Biochar application has emerged as a promising strategy to regulate N dynamics in soil, particularly by reducing N losses through leaching and volatilisation (19, 20). Its porous structure, high surface area and abundant functional groups enhance the adsorption and retention of NH_4^+ and NO_3^- , thereby improving N use efficiency. Biochar application significantly reduces leaching of available N while exerting variable and suppressive effects on NH_3 volatilisation primarily through surface adsorption, modulation of soil pH and alteration of soil microbial community.

Impact of biochar on mineral nitrogen pools

The application of biochar generally leads to an initial decrease in soil inorganic N with a decrease in NH_4^+ - N and NO_3^- - N pool due to microbially induced immobilisation as presented in Table 1. These short-term effects are mostly observed within the first year after

Table 1. Effect of biochar application on nitrogen pools

Soil type	Biochar characteristics	NH_4^+ pool	NO_3^- pool	N_2O emissions	Reference
Sandy	High temperature (> 600 °C)	Decrease	Decrease	Decrease up to 32 %	(18)
Loamy	Low temperature (< 400 °C)	Increase	No change	Increase	(21)
Clayey	Woody feedstock	No change	Decrease (leaching)	Decrease	(1)
Saline	Manure derived	Decrease	Increase (retention)	Decrease	(22)

biochar incorporation. However, the long-term impacts may diminish and even no constant changes in mineral N pools beyond one year due to stabilisation of biochar in soil is also reported with some studies. Short-term biochar addition can cause rapid immobilisation of NH_4^+ , thereby decreasing its availability in the first few days to weeks, mainly in sandy soils. Over longer periods biochar may enhance net N mineralisation in some soils, leading to a gradual increase in mineral N (22).

In acidic soils, short-term biochar effects often include elevated NO_3^- levels due to stimulated nitrification, but this can reverse in long-term scenarios as microbial communities adapt (23). Long-term field trials have shown that biochar produced at high pyrolysis temperature promotes greater N retention through absorption of N onto the biochar, resulting in a reduction in mineral N pool over time, whereas biochar produced at low pyrolysis temperature initially increases the availability of mineral N because of the release of labile pools of N and eventually stabilises the soil mineral N (24–26). In saline-alkaline soils, biochar shows a short-term decrease in NH_4^+ pools, whereas the long-term effects varying by dosage and leading to sustained N availability (27, 28). Overall, short term effects are more variable and pronounced, whereas long term effects tend toward equilibrium in mineral N dynamics.

Nitrification, denitrification and N_2O emission

Biochar enhances nitrification by increasing soil pH and providing a favourable niche for NH_3 oxidising bacteria thereby promoting bioconversion of NH_4^+ to NO_3^- . This effect is greater in acidic soils, where the alkalinity of biochar stimulates nitrifier activity and gene expression (29). Denitrification is often reduced by biochar through reducing NO_3^- availability because of its adsorption and modifying the soil microbial community (30). Biochar decreases N_2O emissions by 16–32 % when combined with N fertilisers (28). In some cases, biochar improves nitrification-mediated N_2O pathways in high-C soils, enhances emission in the short-term (31). Biochar application reduces the abundance of denitrifying bacteria, as seen in reduced *nirK* and *nirS* gene copies, mitigating N_2O emission (30). Overall, the impact of biochar on N_2O is context dependent, with maximum reductions in denitrification-dominated systems (32). Isotope studies show that biochar shifts the N_2O sources from denitrification to nitrification in amended soils (31). These processes highlight the potential of biochar for greenhouse gas mitigation by balanced N cycling (32).

The evidence presented in Table 2, indicates that the influence of biochar on soil N_2O emission is driven by a set of factors such as nature of feedstock, soil type, intrinsic properties like pH and C : N ratio of biochar, pyrolysis temperature, rate of application and other associated soil properties. A significant reduction in N_2O emission was observed with a magnitude of 49 and 51 % by woody and herbaceous biochar respectively (33), reflecting the greater surface area and higher degree of aromaticity of C relative to other feedstocks. Conversely, inconsistent behaviour was noticed in the case of manure-derived biochar showing non-significant effect in some field studies (34). This fluctuating behaviour of manure-based biochar is attributed to the higher residual N and C content of manure and source of manure which reflects that selection of feedstock is the most important determining factor for evaluating the N_2O emission mitigation potential of biochar. Significant reduction in N_2O emission by biochar application was observed both in acidic and alkaline soils, but the magnitude of reduction varied sharply i.e., about approximately 48 % reduction in acidic soil and

Table 2. Effect of biochar on N₂O emission from soil

Property	Category	Effect on N ₂ O emission	Reference
Feedstock type	Wood or herbaceous-derived biochar	Significant reduction in soil N ₂ O emissions, around 49 % (wood) and 51 % (herbaceous biochar)	(33)
	Manure-derived biochar	Variable- no significant effect/ significant increase	(34)
Soil type	Acidic soil	Significant reduction (48 %)	(35)
	Alkaline soil	Significant reduction, smaller magnitude (22 %)	(35)
Biochar pH	High-pH (alkaline) biochar	Significant reduction	(28)
	Near-neutral/lower-pH biochar	Weaker, less consistent reduction	(28)
Pyrolysis temperature	Low temperature (< 550 °C)	Significant reduction	(30)
	High temperature (> 550–600 °C)	Reduced mitigation effect	(28)
Application rate	Moderate (~20 t ha ⁻¹ yr ⁻¹)	Significant reduction (19 %)	(30)
	High (~50 t ha ⁻¹ yr ⁻¹)	Significant reduction, greater magnitude (up to 48 %)	(28)
Soil moisture	Low-moderate (well-aerated, < 60 %)	Significant reduction in N ₂ O emissions by roughly 34–52 %	(36)
	Near-saturated/high (> 70–80 %)	Reduced mitigation effectiveness- N ₂ O emissions rise	(36)
Application with nitrification inhibitors	Biochar alone (no inhibitor)	No significant effect / slight increase- raised N ₂ O emissions by about 4 %	(37)
	Biochar + nitrification inhibitor (e.g., DMPP)	Significant reduction- reduced cumulative N ₂ O emissions by 38 %	(37)
C : N ratio of biochar	High C : N (pristine, plant-derived biochar)	Significant reduction-cumulative N ₂ O emissions up to about 86 %	(38)
	Low C : N (nitrogen-enriched biochar)	Significant increase- nitrogen-enriched biochar with a lower C : N ratio increased cumulative N ₂ O emissions by roughly 157–230 %	(38)

N₂O: nitrous oxide; C: carbon; N: nitrogen; DMPP: 3,4-dimethylpyrazole phosphate.

22 % in alkaline soil (35). This observation is consistent with the liming effect of biochar in acidic soils where the biochar-induced pH increase, causes denitrification.

A clear pattern was observed in the pH of biochar where high-pH biochar showed a significantly higher mitigation potential than near-neutral or lower-pH biochar (30). This reduction in N₂O emission is attributed to the alkalisng capacity of biochar. The pyrolysis temperature also showed a clear pattern, with significant reduction in N₂O emission by biochar produced at low temperatures (< 550 °C) whereas a relatively lower mitigation effect was noticed in high-temperature biochar (> 550–600 °C) (28). This might be due to the persistence of surface functional groups (e.g., carboxyl, hydroxyl) at lower pyrolysis temperatures, which are lost with progressive increase in pyrolysis temperature. The dose-dependent response was also recorded in the present study showing about 19 % reduction in N₂O emission following a moderate rate of application (~20 t ha⁻¹ yr⁻¹), while about 48 % reduction was achieved following a higher rate of application (~50 t ha⁻¹ yr⁻¹) of biochar (30). This suggests that a higher biochar application rate improves soil properties like pH, porosity and adsorption capacity of soil for mineral N. The mitigating potential of biochar was inversely related to the soil moisture showing strongest mitigation under low-to-moderate soil moisture content (< 60 %), while the mitigation potential declined under near-saturated conditions (> 70–80 %) (36). This result is in agreement with the predominance of denitrification under anaerobic, waterlogged condition. A slight increase in N₂O emission of about 4 % was observed under sole biochar application whereas, a significant reduction of about 38 % N₂O emission was caused by combined application of biochar with nitrification inhibitor (37). This finding demonstrates that complementary management practices may improve the benefit of biochar so far N₂O emission is concerned. The contrasting behaviour of biochar was noticed with the C : N ratio. A greater and significant reduction in N₂O emission of about 86 % was observed following application of biochar with high C : N ratio while, biochar with a low C : N ratio resulted in a significant increase in N₂O emission (38).

NH₃ volatilisation and NO₃⁻ leaching

Biochar significantly reduces the loss of NO₃⁻ through leaching. Recent studies indicate that biochar application can decrease leaching of NO₃⁻-N by improving soil adsorption capacity and

enhancing microbial immobilisation. For instance, a 2024 study reported reduced NO₃⁻ leaching due to increased N retention and inhibition of nitrification in deeper soil layers (39). Similarly, biochar amendments reduced NO₃⁻ leaching by about 11.9–21.0 % in Vertisols, especially when combined with organic inputs (40). A greater reduction in leaching of NO₃⁻-N (approximately up to 71 %) has been found in advanced biochar composites by enhancing chemical adsorption and transformation of NO₃⁻. The mechanism is governed by adsorption of NH₄⁺, delayed nitrification and improved soil aggregation, which limits downward movement of N.

The volatilisation loss of NH₃ can be mitigated through biochar application because of its properties such as pH and ash content. This reduction is attributed to increased NH₄⁺ adsorption, cation exchange capacity and improved soil moisture retention. However, the increased volatilisation is observed sometimes under application of high-pH biochar, indicating that nature of feedstock and pyrolysis conditions are critical factors.

Biochar application increases NH₃ volatilisation in alkaline soils due to pH elevation but inhibits it in acidic soil by adsorption (2). In saline soils, suitable biochar rates reduce NO₃⁻ leaching while maintaining N retention without enhancing NH₃ volatilisation (26). Biochar formed from manure is effective in reducing NH₃ emissions from paddy fields by 12–18 % compared to fresh manures (2). NO₃⁻ leaching decreases with pyrolysis temperature, as higher temperatures increase the surface area for adsorption (1). Overall, biochar plays a dual role in minimising N losses by reducing both leaching and volatilisation, thereby improving N use efficiency (1).

The compiled evidence as presented in Table 3, indicates that the effect of biochar on NH₃ volatilisation is highly context-dependent on pH of biochar, nature of feedstock, soil type, pyrolysis temperature and application rate. A global meta-analysis found no significant impact of biochar on NH₃ volatilisation (with an average response ratio (RR) of 0.92 %) (2), whereas a modest average increment in volatilisation was reported in a secondary meta-analysis (RR ≈ 19 %) (41). This difference at the meta-analytic level is reflects that NH₃ volatilisation is not consistently mitigated by biochar. The pH of biochar is one of the important factors governing NH₃ volatilisation. This factor clearly produced one coherent gradient in the table: the NH₃ volatilisation was significantly reduced by acidic biochar (pH < 4) (RR ≈ 42.2 %) (2) and near-neutral biochar

(pH $\approx$ 7) (42), while the alkaline biochar (pH > 9) increased volatilisation significantly (RR $\approx$ 30.8 %) (43). This trend is in line with the mechanism of NH_3 volatilisation, which is governed by pH of the soil and the $\text{NH}_4^+/\text{NH}_3$ equilibrium. It indicates that pH is one of the important decisive properties for predicting the volatilisation mitigating potential of an amendment. Nature of feedstock also influences the NH_3 volatilisation. The biochar derived from wood resulted in a significant reduction in volatilisation (RR $\approx$ 34.6 %) (2), however a significant increase in volatilisation was noticed in straw-based biochar (RR $\approx$ 11.4 %) (43). This result related to the higher pH and ash/mineral content of straw. A variable effect was observed in poultry manure-based biochar (44), indicating the heterogeneity in its composition and often high residual N content. This inconsistency among manure-derived biochar was due to the animal source, processing conditions. The effect of biochar on volatilisation also depended on the type of the soil. A significant increase in volatilisation due to biochar addition was noticed in acid soil (RR $\approx$ +38.38 %) (2). This result is in contrast to the general fact that NO_3^- leaching is the only N-loss pathway in acidic soils. It also reflects the raising of pH towards neutrality and instead reflects that raising soil pH toward neutrality in acidic soil can increase nutrient availability in soil. While the reverse result was observed in flooded soil having near-neutral pH (pH $\approx$ 7.4) showing a significant reduction in volatilisation (RR $\approx$ 12.27 %) (45), similarly the organic C rich soil (> 3 %) also resulted in significant reduction (RR $\approx$ 42.8 %) (2). Among different soil types, the fine-textured soil showed the highest reduction (RR $\approx$ 58.4 %) (41), likely due to greater surface area, more NH_4^+ adsorption

and cation exchange capacity. However, the coarse-textured soil, showed a significant increase in volatilisation (RR $\approx$ 14.18–25.9 %) (46), consistent with lower surface area and adsorptive capacity. An inverse relationship is observed volatilisation process and pyrolysis temperature of biochar. The biochar having low-pyrolysis temperature significantly reduced volatilisation (RR $\approx$ 71.5 %) (44, 47), while that of high-pyrolysis temperature significantly increased volatilisation (RR $\approx$ 73.3 %) (41, 47). This result might be due to biochar-pH pattern, as pyrolysis at high temperature results in more alkaline biochar. Application rate of biochar also showed a similar trend like that of pyrolysis temperature resulting in a significant reduction in volatilisation under low-to-moderate rates (5–15 t ha⁻¹) (2), while an increment in volatilisation was noticed under high application rates (> 40 t ha⁻¹) (41).

The effect of biochar on NO_3^- leaching as depicted in Table 4, shows that the magnitude of the effect of biochar varies considerably depending on the nature of feedstock, soil type, biochar pH, pyrolysis temperature and rate of application. A meta-analysis of 88 studies reported an overall 13 % reduction in NO_3^- leaching with biochar application (5), while a larger predicted decline of 12–29 % (49) was projected in a global meta-analysis. Among the feedstocks mentioned in the table, straw-derived biochar produced the highest reduction of NO_3^- leaching ($\sim$ 45 %), in line with its greater NO_3^- adsorbing ability because of the presence of higher density of oxygen-containing surface functional groups. However, manure-derived biochar showed no significant effect, likely due to its higher ash and salt content, which increases the electrical conductivity of

Table 3. Effect of biochar on ammonia volatilisation in soil

Specific factor	Category	Effect on volatilisation	Reference
Overall trend	Global meta-analysis	No significant impact (on average RR-0.92 %)	(2)
	Secondary meta-analysis	Increase in volatilisation (average RR-19 %)	(41)
pH of biochar	Acidic (pH < 4)	Significant reduction (RR- 42.2 %)	(2)
	Alkaline (pH > 9)	Significant increase (RR-30.8 %)	(43)
	Near-neutral pH ($\sim$ 7)	Significant reduction	(42)
	Wood-based	Significant reduction (RR-34.6 %)	(2)
Nature of feedstock	Straw-based	Significant increase (RR-11.4 %)	(43)
	Poultry manure-based	Variable	(44)
	Livestock manure-derived biochar	Significant reduction (RR-45 %)	(48)
	Acidic soil	Significant increase (RR-38.38 %)	(2)
Soil type	Paddy / flooded soil (neutral, pH $\sim$ 7.4)	Significant reduction (RR-12.27 %)	(45)
	Soil rich in SOC (> 3 %)	Significant reduction (RR- 42.8 %)	(2)
	Fine-textured soil	Significant reduction (RR-58.4 %)	(41)
	Coarse-textured soil	Significant increase (RR-14.18 to 25.9 %)	(46)
Pyrolysis temperature	Low	Significant reduction (RR-71.5 %)	(44, 47)
	High	Significant increase (RR-73.3 %)	(41, 47)
Rate of application	Low to moderate (5–15 t ha ⁻¹)	Significant reduction (RR-33.8 %)	(2)
	High (> 40 t ha ⁻¹)	Significant increase	(41)

RR: response ratio.

Table 4. Effect of biochar on nitrate (NO_3^-) leaching from soil

Property	Category	Effect on nitrate (NO_3^-) leaching	Reference
Feedstock type	Meta-analysis (88 studies)	Overall, 13 % reduction	(5)
	Global meta-analysis	12–29 % predicted decline globally	(49)
	Straw-derived biochar	Significant reduction about 45 %	(50)
	Manure-derived biochar	No significant effect / reduced effectiveness	(50)
	Poultry manure	35 % reduction in cumulative leaching	(51)
	Maize stover	26.46–26.82 % reduction	(46)
Soil type	Apple branch	8.3–17 % reduction	(52)
	Acidic soil (e.g., acidic red soil, podzolic soil)	Significant reduction (33–49 %)	(50, 53)
	Saline-alkaline soil	significant increase in nitrate leaching by 10–18 %	(50)
Biochar pH	Alkaline biochar applied to acidic soil	Significant reduction (up to 38 % over 90 days)	(50)
	High-pH biochar applied where soil pH exceeds the biochar's point of zero charge	No significant effect / weakened retention	(50)
Pyrolysis temperature	Moderate temperature ($\sim$ 500 °C)	Significant reduction	(50)
	High temperature ($\sim$ 700 °C)	Reduced effectiveness	(50)
Application rate	Moderate/split application (repeated small doses)	Significant reduction about 20 %	(50)
	High single dose (e.g., 40 t ha ⁻¹ ; or 10 % v/v in podzolic soil)	significantly reduced NO_3^- leaching by 48.6 % in an acidic podzolic soil	(50, 53)

soil and thereby interferes with NO_3^- retention (50). The reduction in leaching was about 35 % with poultry manure (51), 26.46–26.82 % by maize stover biochar (46) and 8.3–17 % by biochar derived from apple branch (52).

This study indicates that straw-based feedstocks with greater surface functionality appear most suitable for mitigating NO_3^- leaching. The highest reduction of NO_3^- leaching was reported in acidic soils in the range of 33–49 % (53). This is coherent with the liming action of alkaline biochar resulting in an increase of soil pH in acidic conditions which favours NO_3^- retention. In contrast, the reverse trend was noticed in the saline-alkaline soils showing a significant increase in NO_3^- leaching of 10–18 % (50). This might be due to the elevated pH and electrical conductivity of an alkaline soil following biochar application which reduces NO_3^- retention. The findings of the pH of biochar indicated a significant reduction in NO_3^- leaching up to 38 % upon application of alkaline biochar in an acidic soil (50), whereas no significant effect was noticed upon application of a high-pH biochar to a soil whose pH already exceeded the biochar's point of zero charge (50).

This indicates that the magnitude of the electrostatic interaction of biochar with the negatively charged NO_3^- ion is not fixed but depends on the relative pH of the receiving soil. A significant reduction in NO_3^- leaching was observed in soil receiving biochar pyrolysed at moderate temperature (~ 500 °C), while the biochar pyrolysed at higher temperature (~ 700 °C) showed reduced effectiveness (50). This aligns with the literature, where moderate temperature tends to provide a balance of surface functional groups and surface area suitable for NO_3^- sorption, whereas higher temperature results in loss of oxygen-containing groups and increase aromaticity. A significant reduction in NO_3^- leaching of about 20 % was observed in the split-application method (50), while a larger reduction of NO_3^- leaching of 48.6 % in acidic soil was observed following a high single-dose application (53).

In the present era, the scientific literature on the influence of biochar on N dynamics in soil has expanded exponentially, driven by global imperatives for climate change mitigation and soil health restoration. A bibliometric analysis of this domain is therefore essential to systematically map the evolution of research output,

identify key thematic clusters (such as adsorption mechanisms, microbial-mediated transformations and greenhouse gas emissions), pinpoint influential contributors, journals and geographic hotspots and objectively reveal emerging trends alongside persistent knowledge gaps such as limited long-term field validations in diverse edaphic conditions or under varying climatic regimes.

Against this backdrop, the present study will undertake a bibliometric literature review on the influence of biochar on N dynamics in soil across the world with the help of Scopus-indexed literature that was published in 2017–26. The paper will set out to analyse the increase of publication and the citation patterns, the most predominant sources, institutions, authors and nations, keyword structures and thematic developments and also map the collaboration and intellectual network in the discipline. In such a way, this study gives an organised review of the way biochar research has evolved over the past years and identifies significant knowledge clusters, arising themes and research directions. By doing so, the article can be said to make a contribution to the comprehension of biochar as a significant issue of soil management as well as to the science-based and sustainable methods of soil improvement. By integrating this quantitative overview with the salient findings of the present research, the bibliometric assessment provides a robust contextual framework that underscores the relevance of our experimental investigations into biochar-mediated N retention and loss pathways.

Publication growth and citation dynamics

Fig. 3 illustrates scientific production, average citations in the year of publication and publication life cycle of biochar soil-amendment studies. The figure shows that there has been a consistent increase in the number of publications per year in the course of the study period, which means that biochar has evolved to be a more than an emergent subject into a research field of its own that continues to grow rapidly. Simultaneously, the relatively high average citation rates in the past and low in the recent years are also an indication of a normal effect of time citation, as older studies have had increased time to receive scholarly attention. This trend can be interpreted against the background of the literature that was developed early on

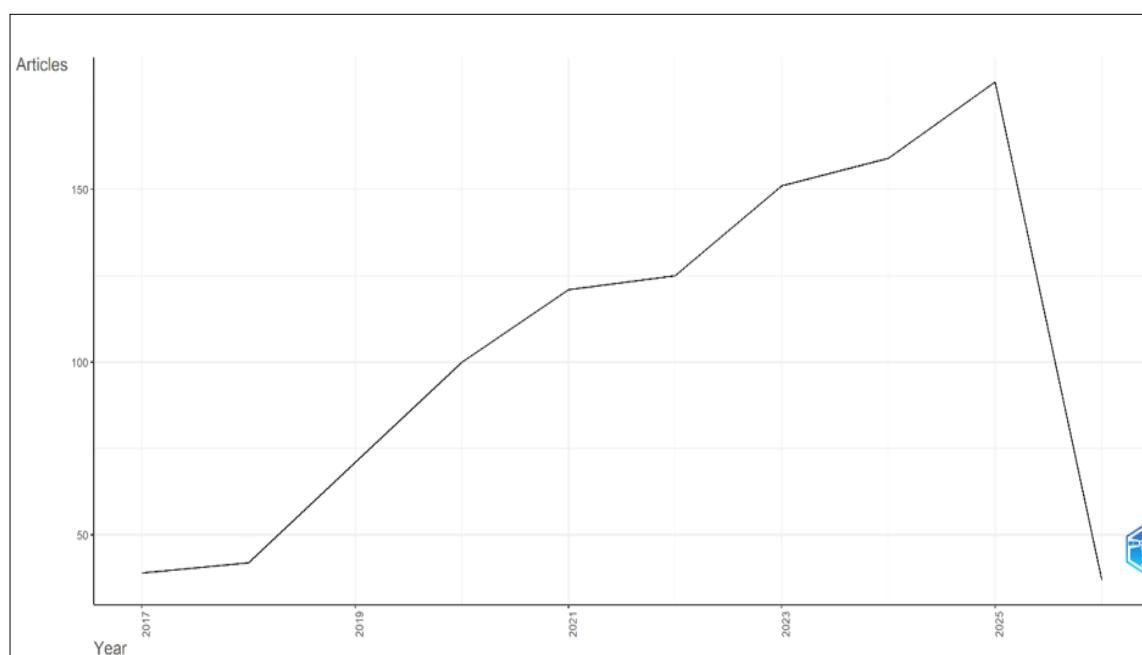


Fig. 3. Annual publication and citation trends.

to make biochar a scientifically significant approach to soil management. Biochar received a lot of focus due to its capacity to enhance both soil characteristics and C and N stabilisation in the soil of terrestrial ecosystems (54, 55). Work on biochar re-evaluations also positioned biochar as a versatile material that could be used in the retention of N, soil conditioning and environmental management, which also might have led to the increase in the numbers of publications in the field later. Accordingly, not only does the trend in Fig. 3 represent a bibliometric indication of rising output, but it is also the demonstration that the initial studies carried out in the mid-2000s provided the intellectual foundation over which the further growth of the biochar studies took place.

Fig. 4 introduces the cumulative growth curve of the publications and demonstrates a gradually increasing, but rapidly growing direction, particularly in later years of the period of the study. It means that the research on biochar has not developed sporadically but has progressed steadily, which hints at the ongoing integration of the sphere of soil science, agronomy and environmental research. The cumulative trend also suggests that the research on biochar did not focus narrowly on C-sequestration but expanded to the other areas like enhancement of soil fertility, transformation of N and soil biological activities. Earlier reviews support this interpretation. Previous studies have stressed that biochar cannot be treated as a storage of C only, although it is a more comprehensive soil and climatic intervention to be investigated systematically at physical, chemical and biological levels (56). Later on, the impact of biochar application to soils was critically assessed and emphasised its impact on the properties and functions of the soil as well as identified that more evidence was required in various soils and production systems (57, 58). These previous investigations when combined help explain the steepness of the cumulative curve in Fig. 4 as early conceptual and review articles established the broad scope of biochar research, the discipline branched out at a massive pace and began to sustain research interest.

Source structure and journal influence

In Fig. 5, the most pertinent sources that release the research on effect of biochar on N dynamics in soil can be seen and the literature

is concentrated in a small number of journals, whereas the rest of the output is distributed across a significantly broader, dispersed range of sources. This trend shows that even though biochar studies are interdisciplinary, there is a familiar list of journals that have taken the position of the primary publication sources of the research. This trend is common in a growing yet rapidly structured field of research whereby the scholars repeat the journals that are closely affiliated with soil science, agronomy, environmental management and sustainability. The prevalence of these most popular sources indicates that biochar studies have attained thematic coherence and have developed stable means of communication with scholars. The given finding also complies with the principles of bibliometrics discussed by earlier studies, according to which the analysis of sources contributes to the identification of the communication structure of a discipline and it also coincides with the latest biochar bibliometric papers, which demonstrate that only a small number of journals involve a significant proportion of the total publications in the given field (57, 59). Fig. 6 depicts the major sources in the Bradford's law in which a small nucleus of journals provides a disproportionately large contribution to the total literature with successively larger areas of source of less productive contribution. This distribution supports a typical Bradford-type scattering distribution, which is typically found in bibliometric studies and shows that there is a journal core of the field. The presence of a small group of major journals in the current case indicates that the research on the influence of biochar on N stock in soil has become disciplinarily more centralised, although other related disciplines like environmental engineering, waste management and climate research still have input in the research. The discovery of a Bradford core is significant as it aids in understanding the location of where the core of the scientific discussions is occurring and where future researchers would probably discover the greatest concentration of pertinent work. This finding is in line with the classical reading of the law of Bradford as a trend of source convergence to the subject matter and is also compatible with recent bibliometric studies, such as Bibliometrix where a small group of journals usually constitutes the communication core of a study field (57). More recent biochar bibliometric analyses have also described a definite core-periphery

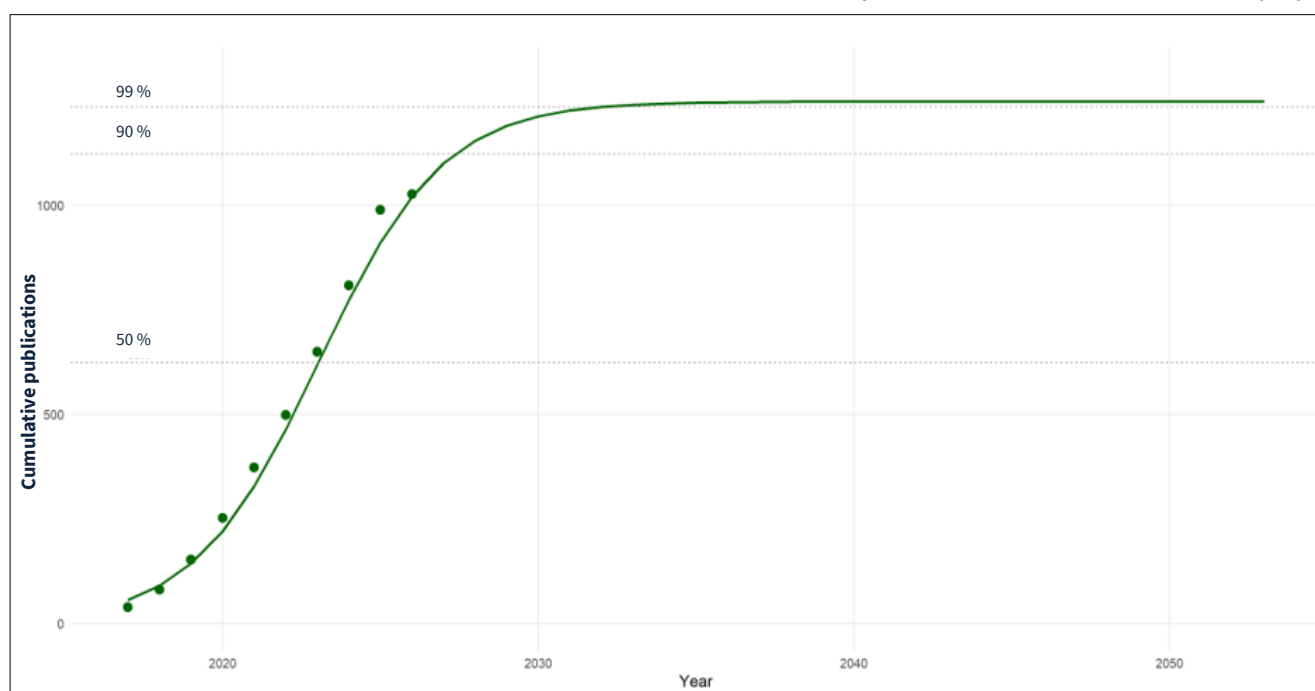


Fig. 4. Cumulative publication growth.

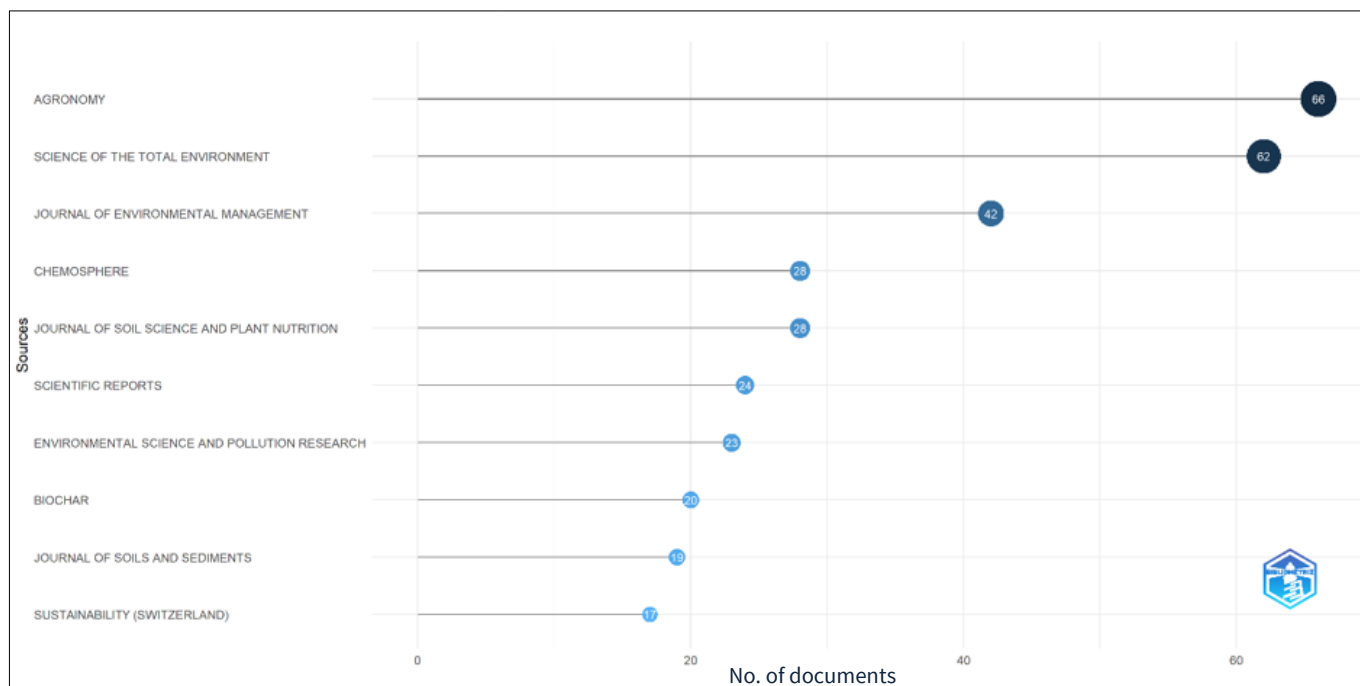


Fig. 5. Most relevant sources.

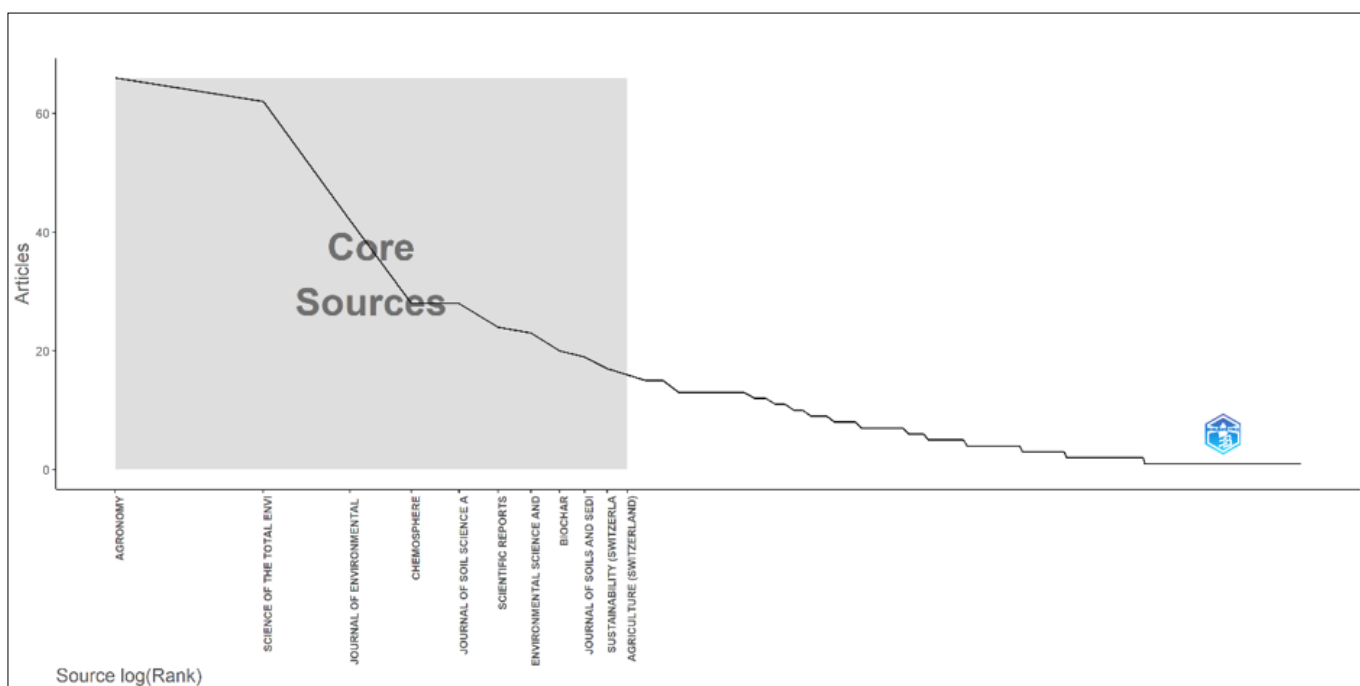


Fig. 6. Bradford's core journals.

journal pattern, which supports the perception that the discipline now has a recognisable and publication center (biochar in the circular bioeconomy study) (59).

Fig. 7 presents the sources input by their production with time and it can be seen that the involvement of journals in the study of biochar has changed significantly within the study period. This figure indicates that there are journals that came into the field earlier and have kept a regular publishing profile and others seem to have become more active only during the recent expansion time. This trend over time suggests that communication of the field has increased in diversity as time went by: the conceptual and review work was probably formative in early journals and more recent or more intensively-emerging journals represent the broadening of biochar research into other uses like remediation, nutrient management, microbial ecology and climate-smart agriculture. The fact that some journals have remained active over several years also

aids in indicating that they have been a stable system of developing the field. This explanation is consistent with bibliometric research results that temporal source analysis can disclose the historical core and the developmental directions of a field (57). It is also in line with the recent bibliometric investigations of biochar, which note that a small number of well-established journals have been at the heart over the years, but that the recent explosion of publications has brought in more diverse sources as the discipline becomes more interdisciplinary and application-focused (59, 60).

Leading institutions, authors and countries

Fig. 8 provides the most relevant affiliations in biochar studies and demonstrates that the number of publications is clustered in a rather small number of institutions, which means that the area is influenced by a group of highly active research centres. The high level of concentration indicates that the biochar research has attained good institutional foundations, which are probably

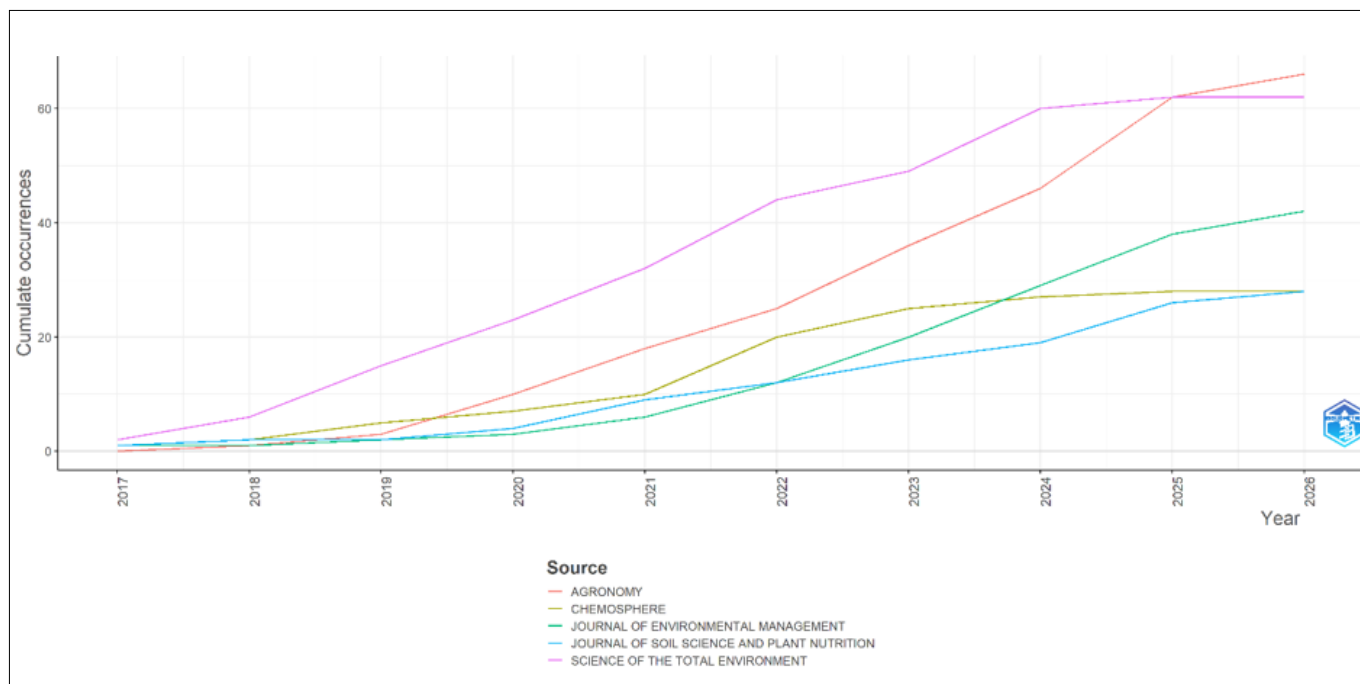


Fig. 7. Source production over time.

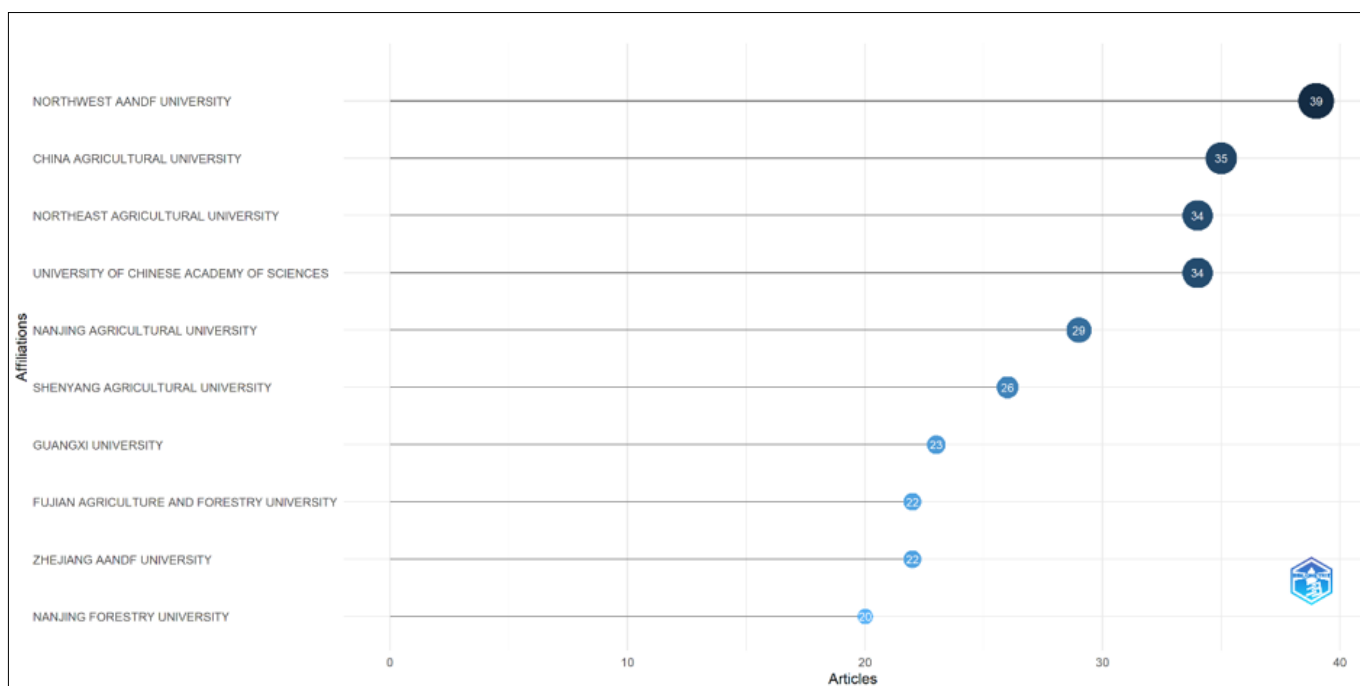


Fig. 8. Leading affiliations.

facilitated by special laboratory capacity, extensive soil testing capabilities and multidisciplinary cooperation among researchers in the agronomy, soil science, environmental science, climate studies. The prevalence of leading affiliations is also indicative of the fact that biochar studies frequently demand technical capacity in the field of pyrolysis, soil characterisation, nutrient analysis and microbial evaluation which is more likely to be available in well-established universities and research institutes (6). Similar patterns have been observed with bibliometric studies, in which big affiliations often become centres of scientific output and power within a discipline. The institutional dominance represented in Fig. 8 in the context of biochar is in line with the previous underlying research that has seen biochar as a noteworthy research field in soil fertility, N management, C sequestration and environmental sustainability, therefore, promoting institutional commitment in this subject (6, 19, 61).

Keyword structure and thematic evolution

Fig. 9 shows the most relevant keywords in the literature of biochar and soil N and also determines the conceptual vocabulary which dominates the field. The prevalence of soil, biochar, N, microbial community, C and fertility related words demonstrate that the body of knowledge is highly focused on the improvement of the soil, the dynamics of N and biological processes. This trend indicates that the discipline has moved past the idea of biochar only as a C-sequestration product and has begun to consider it as a multifunctional amendment correlated with soil health, nutrient-use efficiency, as well as ecosystem functioning. The prevalence of these keywords is not surprising given previous background reviews that have put into the spotlight the effects of biochar on soil physical, chemical and biological characteristics and its possible utilisation in enhancing fertility as well as making the environment sustainable

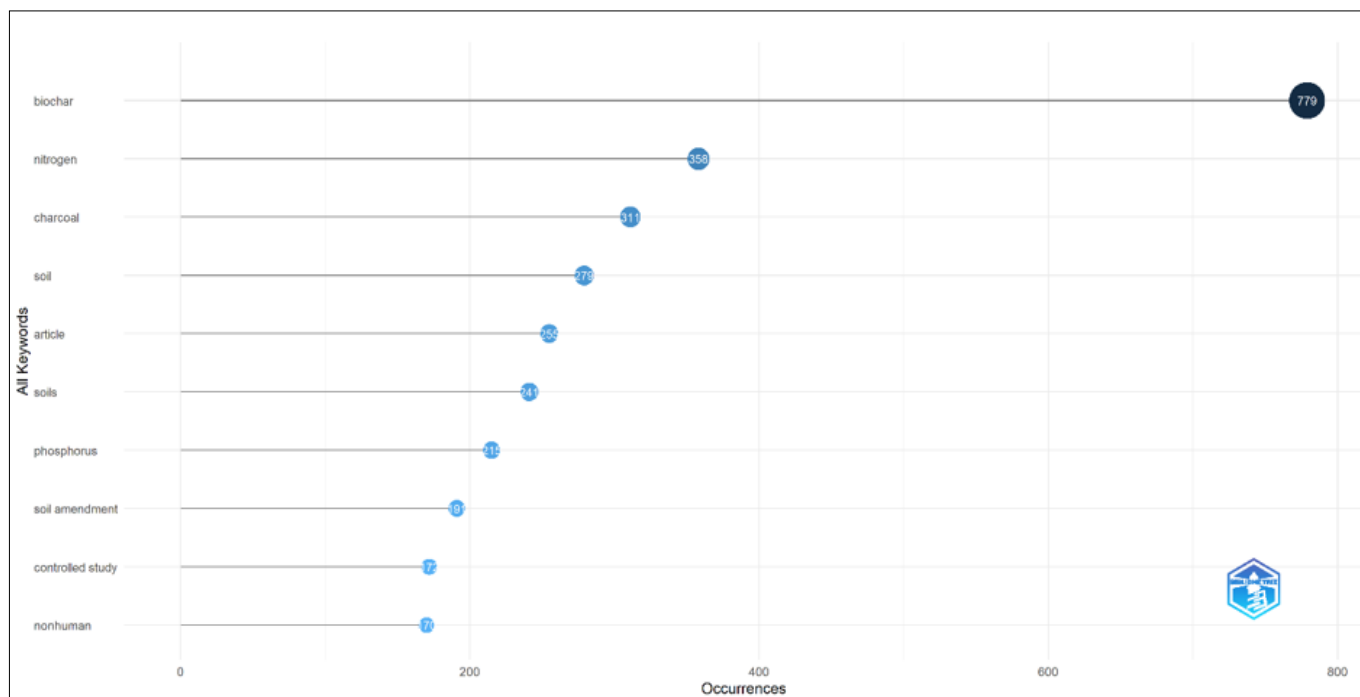


Fig. 9. Most relevant keywords.

(6, 58, 61). These findings confirm that the conventional conceptual framework of the discipline is still based on the key themes developed by early biochar research, as well as showing a trend towards more process-based subjects including microbial communities and nutrient cycling.

Using Fig. 10, the trend topics in the literature are represented and the themes that were on the rise at certain times are highlighted. The recent appearance of issues to do with microbial community, N dynamics, adsorption, soil properties, remediation and sustainability argue that the discipline has endured a gradual transformation and one that has long been more focused on general exploratory studies as opposed to more specific studies, based on mechanisms and aimed at applications. The trend-topic analysis is very practical since it shows the problems, which recently received the attention of a collective of scholars, thus pointing to the front line of research in the field. Here, the growing importance of biologically and agronomically oriented issues implies that the

studies on biochar are becoming more interested about the material behaviour in the field conditions and the interaction between the material and soil biota, nutrients and other environmental factors. This interpretation is compatible with the recent reviews which indicate that there was an increase in interest in biochar-mediated alterations in microbial dynamics, N retention, soil resilience and sustainable crop production (11, 12, 62). The number thus denotes that modern biochar studies are getting integrative, relating soil mechanisms to workable sustainability results. The thematic map classifies research themes based on their centrality and development and thus differentiates between motor themes, basic themes, niche themes and emerging or fading themes (Fig. 11). The location of the major biochar-related topics in the map offers an understanding of the intellectual structure of the area. High centrality and density themes can be viewed as well-developed and significant and high centrality and less developed themes can be viewed as the foundational ones which are significant but are in the

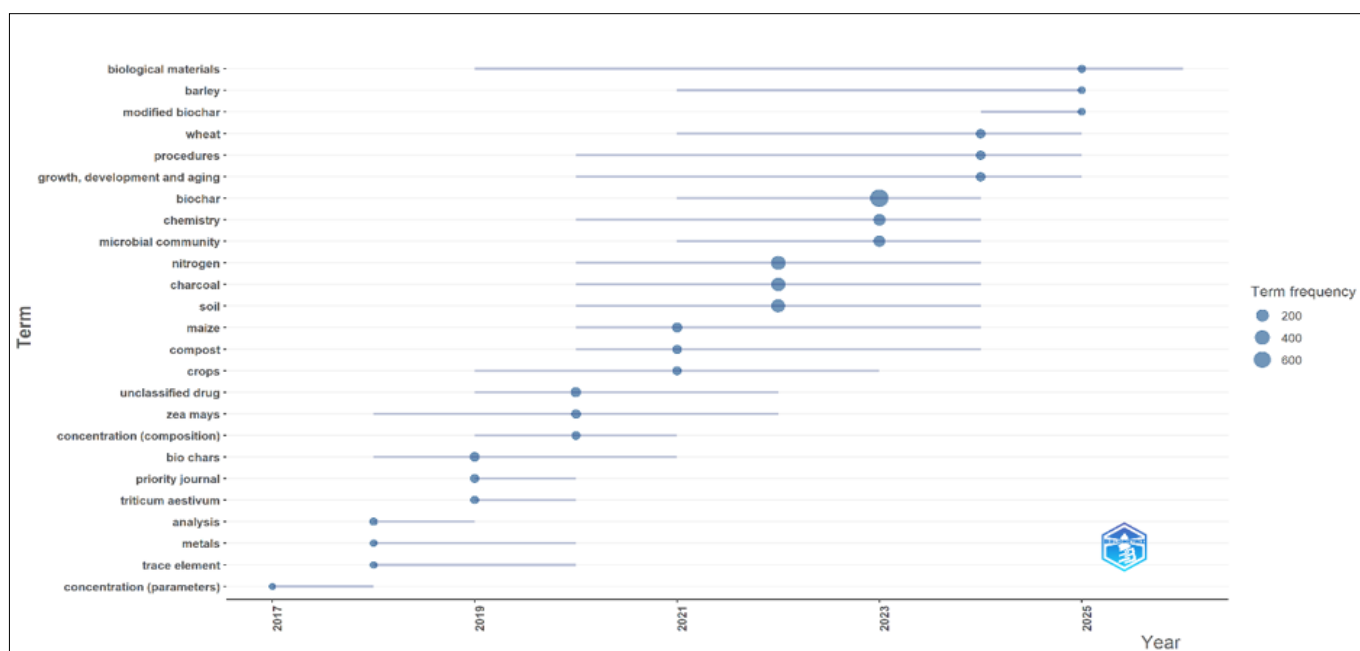


Fig. 10. Trend topics.

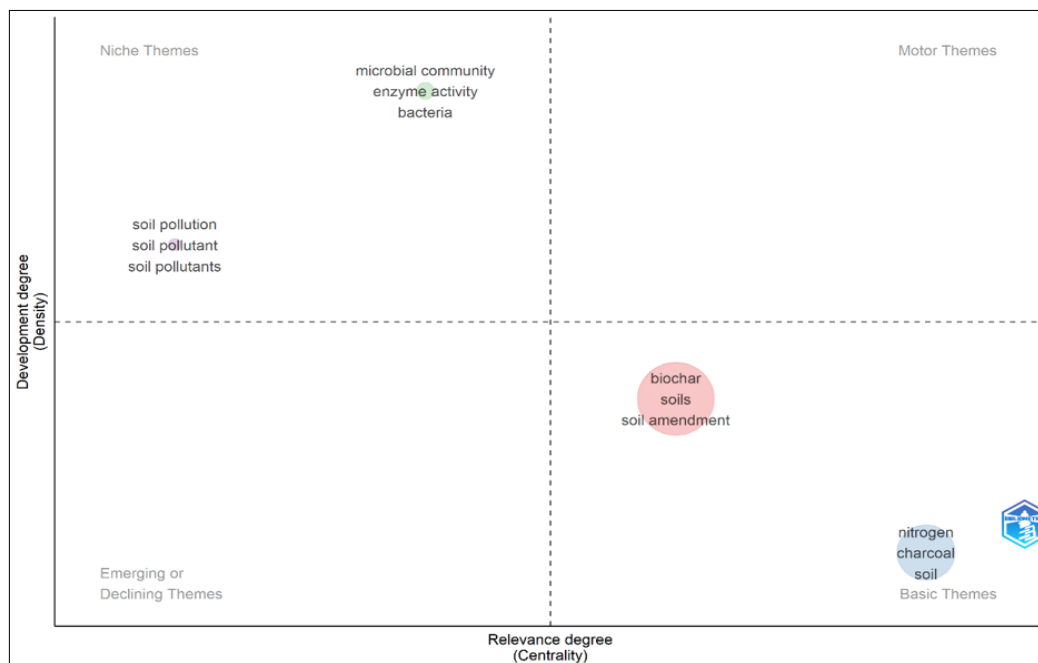


Fig. 11. Thematic map. Source: Biblioshiny application.

process of development. Thematic map, in the current instance, probably represents the core position of soil amendment, fertility, nutrient dynamics and environmental management, as well as it suggests the formation of more specific or fast-growing themes of microbial interaction, remediation and stress environment. This form of thematic organisation is in line with science-map methods outlined previously (63, 64) and implemented in Bibliometrix (57). The thematic map will also complement the larger body of literature that indicates that the area has become structurally divided, with central themes that were identified by the initial reviews and the new special topics that have arisen with the expansion of the evidence base (59).

Fig. 12 shows the conceptual structure map that categorises the keywords in clusters according to their co-occurrence and, thus, demonstrates the key conceptual areas in biochar soil-N studies. The clustering pattern probably divides themes concerning soil fertility and nutrient management, microbial and biological reactions, environmental remediation and sustainability-focused applications. This shows the field is intellectually structured into a number of interrelated sub domains as opposed to being a single undifferentiated subject. The conceptual structure map thus acts as a good testimony to the presence of interdisciplinarity, as well as demonstrates that the different branches of biochar research are nonetheless connected due to the similarity of interest in the improved performance of soil and the environment. This clustering is not surprising in a subject that borders on chemistry, biology, agronomy and environmental science and it is clear that it is in line with prior reviews that characterise biochar as a multi-purpose material with effects that cross numerous processes in soil and ecosystem (9, 64, 65, 66). In this regard, The field has acquired conceptual depth as well as thematic consistency, which is a sign of a developing and intellectually organised research domain (Fig. 12).

Collaboration, intellectual structure and knowledge networks

The global collaboration map demonstrates that research on biochar soil-amendment is represented geographically, but lacks uniform connections, with a few countries serving as the primary links in global scientific communication (Fig. 13). This trend suggests that the domain has gained a high worldwide presence, but the

collaboration intensity is particularly high among certain countries which probably have the developed research facilities, biochar initiatives and sustainable international relationships. In a subject like biochar, whereby people express different reactions based on the feedstock, soil type, climate and the cropping system, cross-country collaboration is particularly useful since it enables comparison of findings across agroecological contexts. The collaboration map hence indicates that the discipline is not only geographically expanding but is also establishing comparative and transnational evidence. This meaning aligns with bibliometric analysis results that international cooperation tends to increase knowledge diffusion and visibility of the field (67) and recent scientific studies on biochar scientometrics indicate that the international research on biochar has become more collaborative and internationally distributed (59). A similar pattern is also supported by foundational reviews that stressed the context-specificity of biochar performance and the need to provide evidence of it in a wide variety of settings at an early stage (7). A keyword co-occurrence network, provides the conceptual relationship of the most common terms associated in the data set (Fig. 14). The fact that the keywords are clustered together shows that biochar studies are structured around a few closely related themes, including, soil amendment, N dynamics, microbial community, C sequestration, remediation and crop response. This establishes that the field possesses a conceptual central core and there are also a number of thematic branches. Co-occurrence networks are useful in bibliometric terms as they demonstrate not only the frequency of a term but provide information about the connections between ideas in the literature. In this case, the network proposes that the area of biochar research has become a combined field with agronomic, biological and environmental issues overlapping. This is in line with previous reviews which had characterised biochar as a multipurpose product that influenced the physical, chemical and biological processes in soils as opposed to a unifunctional amendment (6, 58, 61). It is also consistent with subsequent mechanism-based syntheses that biochar research is becoming more and more joined in terms of microbial ecology, nutrient transformations and plant responses in a unified conceptual framework (9).

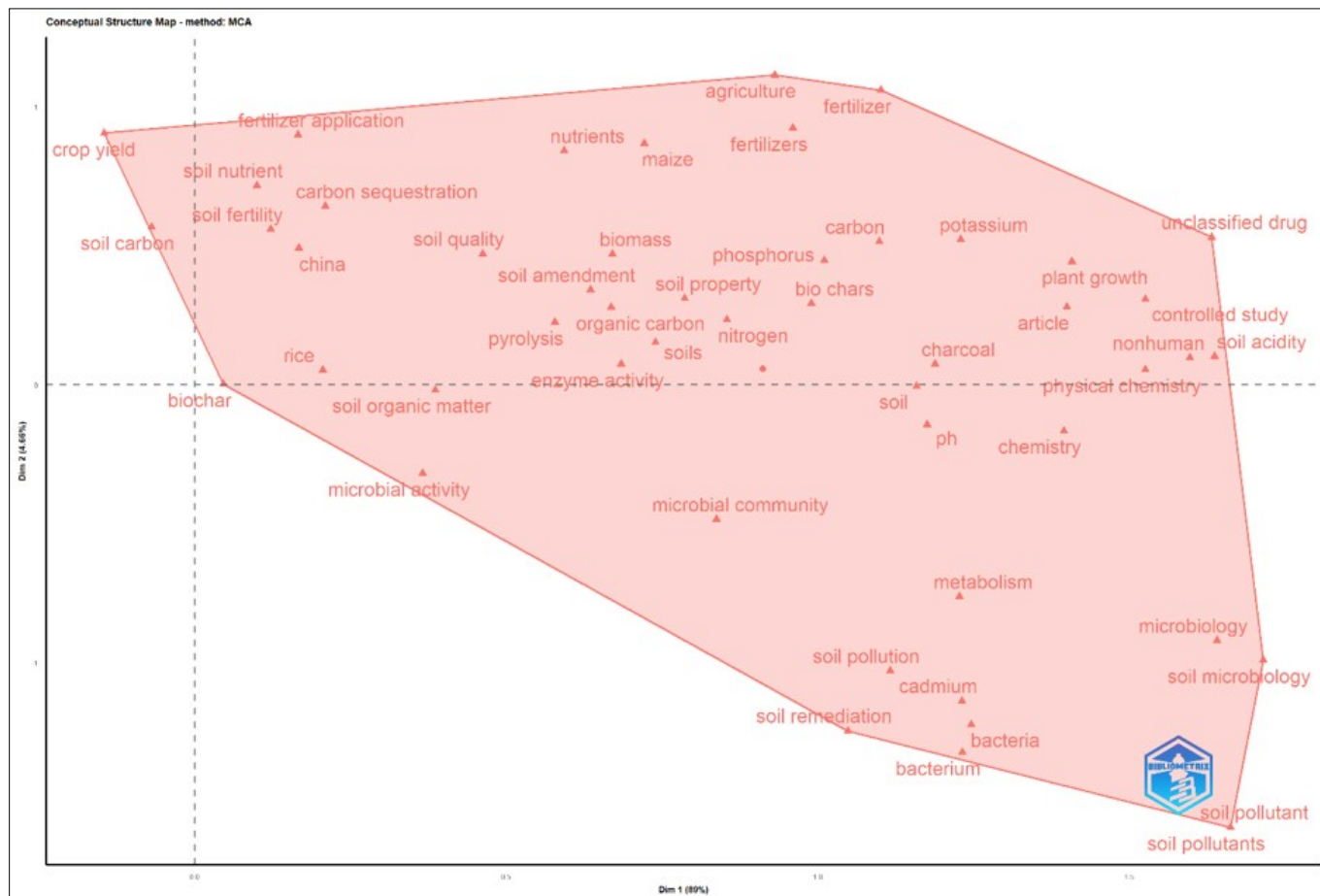


Fig. 12. Conceptual structure map. Source: Biblioshiny application.

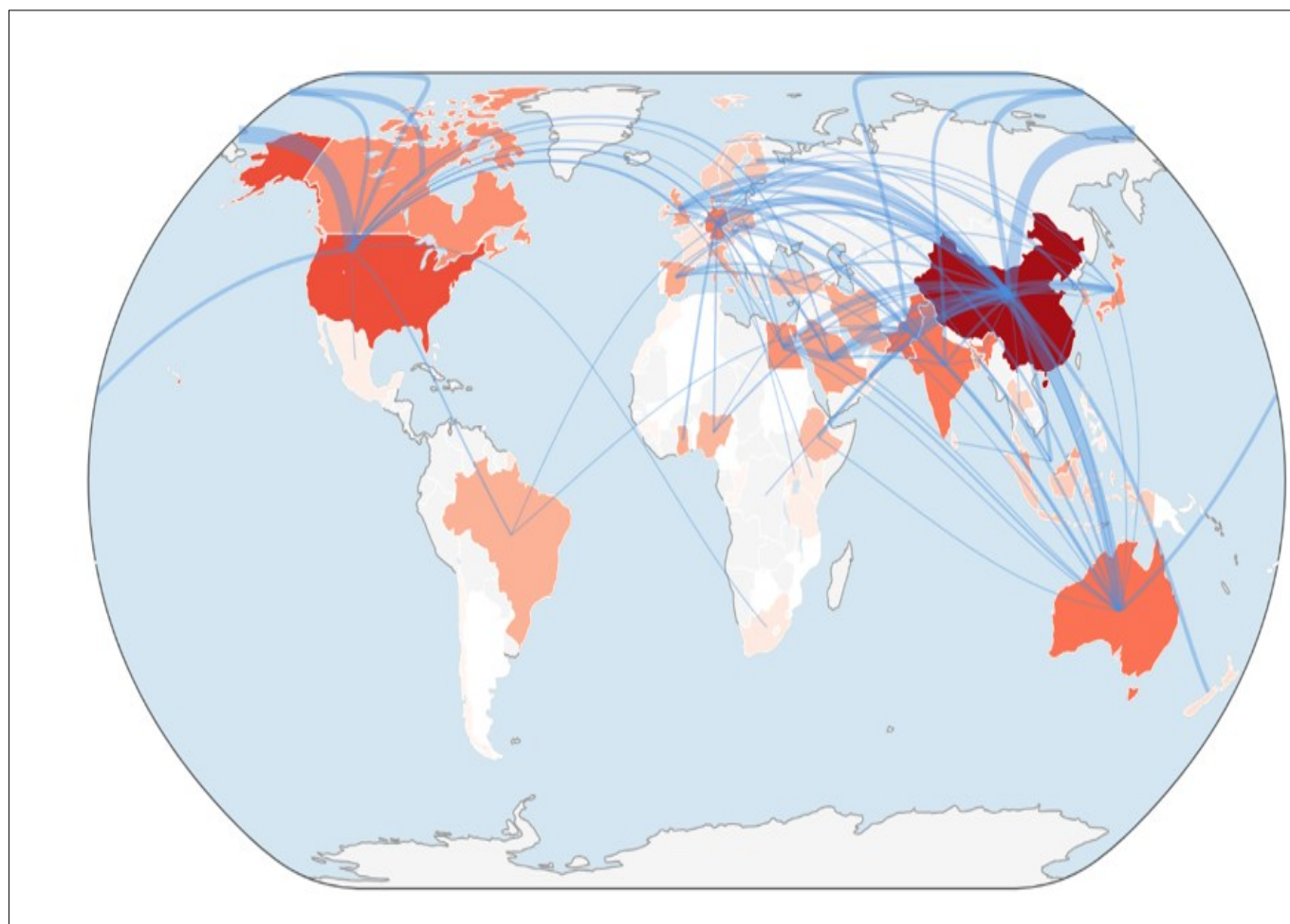
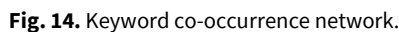


Fig. 13. Country collaboration map. Source: Biblioshiny application



microbiology, crop science and environmental assessment. The network of authors thus suggests that interdisciplinary collaboration and repetitive academic collaborations have aided the evolution of the discipline. This tendency is consistent with the overall bibliometric knowledge that collaboration networks get more formal as a discipline grows and develops a more powerful research pool (57, 67). This collaborative pattern in the case of biochar can also be interpreted as the evolution of a field over time, since the initial conceptualisation of the field was early and focused on reviews rather than on more specialised and experimentally intensive research.



Results and Discussion

The data presented in Tables 2–4 reveals that all the associated properties like nature of feedstock, soil type, pH of biochar, pyrolysis temperature and application dosage interact in different ways with the chemistry behind NH_3 volatilisation, N_2O emission and NO_3^- leaching.

The pH of the biochar is one of the important properties affecting different loss pathways of N in soil. Acidic-neutral biochar significantly mitigates the loss of N so far NH_3 volatilisation is considered (2, 42) however, the alkaline biochar increases the loss of NH_3 , as the $\text{NH}_4^+/\text{NH}_3$ equilibrium shifts towards the volatile form under higher pH (43). On the other hand, the high-pH (alkaline) biochar results in significant reduction in N_2O emission, because the complete denitrification to gaseous N (N_2) is achieved under elevated pH rather than N_2O (28). The effect of pH of biochar is conditional so far leaching is considered. The alkaline biochar causes significant reduction in NO_3^- loss only when it is applied to acidic soil (50). This indicates that all the three pathways of loss can't be optimised by the pH of biochar only. The effect of pyrolysis temperature on N loss is more consistent across three different pathways. A significant reduction in both NH_3 volatilisation and N_2O emission is achieved through low-temperature biochar (28, 44, 47) whereas the high-temperature biochar increases the loss. In case of NO_3^- leaching, moderate-temperature biochar performs better in mitigating the loss than that of high temperature one (50). Moreover, it suggests biochar produced at low-to-moderate pyrolysis temperature can be effectively utilised for N management in soil, because it preserves the oxygen-containing functional groups in the surface.

The nature of feedstock also influences N loss in soil in different pathways. The wood-based biochar significantly mitigates N_2O emission and NH_3 volatilisation (2, 33) while, straw-based biochar increases volatilisation. However, the straw-based biochar significantly reduces leaching due to higher NO_3^- retention because of greater density of oxygen-containing functional groups (50). Manure-based biochar is showing variable results in cases of NH_3 volatilisation, N_2O emission and NO_3^- leaching due to higher content of salt and ash (44, 50). It suggests that the manure-based biochar can't be used for soil N management until it is specifically modified or blended. A sharp variation is observed in the rate of application of biochar and it is the important practical takeaway for the review. The higher application rate consistently reduces N_2O emission (28) and NO_3^- leaching in acidic soils (53), while it enhances NH_3 volatilisation (41). It means the rate of application of biochar should be pathway specific as well as site-specific. The fine-textured, organic-C-rich soil shows a significant reduction in NH_3 volatilisation (2, 41), while the loss of NH_3 increases in coarse-textured soil. Acid soil significantly mitigates N_2O emission (35) and NO_3^- leaching in soil (53), but it increases NH_3 volatilisation. This suggests the texture and pH of soil are the major decisive factors for N management.

The current bibliometric analysis demonstrates that the interest in the study of biochar as a soil amendment has grown quickly and been systematised into more organised, interprofessional and thematically varied throughout the years 2017–26. The steep increase in scientific output of the scientific community in annual scientific production shows that biochar is no longer viewed as a refined C-sequestration material, but rather a multifunctional amendment that has wide application in the improvement of soil fertility, nutrient retention, microbial processes

and sustainable management of agricultural practices. This trend resembles the development that had been expected in previous conceptual works, which placed biochar at the balance point between soil enhancement and ecological sustainability (54, 61). The increment in the number of publications is another indicator of the fact that the field is not in the exploratory stage anymore, but there is the substantial and constantly growing amount of empirical and review-based evidence that support the field (68, 69).

The other significant result of the research is the formation of the definite source structure where the limited number of journals can be considered the primary channels of communication of biochar research. The presence of core journals and a Bradford-like distribution suggest that the field has achieved what are sometimes identified as print journals and this is a typical indicator of disciplinary solidarity (70). Simultaneously, the dissemination of works in a greater number of journals can indicate that the study of biochar continues to be interdisciplinary, with contributions extending not only via agronomy, soil science, environmental management and sustainability studies. This is a balance of both concentration and dispersion, which is significant, as it indicates that the field is both coherent and outward-looking. As a practical matter, it implies that biochar studies have established a steady academic core and remain involved in more general scientific discussions on climate-smart agriculture, nutrient management and ecological repair (71, 72).

It can also be seen in the analysis that the discipline is highly influenced by a relatively few institutions, authors and nations, which suggests that there are well-established research centres and powerful scholarly networks. This kind of concentration is typical of technically challenging fields of research, in which prolonged experimentation, state-of-the-art laboratory resources and cross-functional experience are to be applied. Nonetheless, the patterns of collaboration and co-authorship indicate that the biochar studies are not confined to the individual centres of excellence; instead, they are becoming more backed by the national and global collaboration (73, 74). It is especially important since the biochar performance is highly context dependent and depends on the feedstock and pyrolysis conditions, soil type, climate and the cropping system. Thus, wider cooperation will strengthen the comparative advantages of the literature and raise the capacity of the discipline to produce both regionally and globally applicable knowledge. The degree of international co-authorship in the dataset which has been observed can be seen as supporting the opinion that biochar studies are increasingly becoming an integrated world field and not a collection of discrete local studies (75, 76).

One of the most important contributions that the study has made is its ability to demonstrate how the thematic focus of biochar research has changed over the years. The keyword structure, the trend-topic analysis, the thematic map and the conceptual structure map are all signs that the field has ceased to deal with broad topics, like soil amendment, C and fertility and has been transitioned into more specific and process-oriented topics, like microbial communities, N dynamics, adsorption, remediation and soil biological health. Such thematic development is indicative of the fact that the field has grown scientifically in its early days the main interest of the field was to define the value of biochar and to determine its wide environmental and agricultural value, but more recent work is more concerned with mechanisms, context specificity and result of application. This transition is aligned with subsequent

literature review that noted the fact that biochar does not yield homogeneous effects and that its functionality is based on complicated interactions between soil properties, plant systems, management circumstances and amendment properties (9–11).

The network analyses also support the fact that the biochar research has built a firm intellectual foundation but still maintains a varied thematic focus. The co-occurrence keyword and conceptual clusters indicate that the literature is structured in terms of interconnecting areas, as opposed to individual issues (76, 77). This thematic growth and intellectual growth are a valuable sign of a healthy and growing research discipline. It is an indication that, though there are new themes that are being developed, the field has not been conceptually torn. Rather, biochar studies seem to be developing within the specialisation context based upon a shared platform of thoughts on the enhancement of soil quality, N retention, nutrient regulation and environmental sustainability (61, 78).

Combined, this evidence suggests that biochar as a soil amendment has reached the maturity yet fast evolving research study. The literature is growing in size, becoming concentrated in fundamental journals and institutions, branching into new thematic areas and growing in collaboration, both at the national and international levels. Pragmatically, this development is a manifestation of the increased awareness of biochar as a multifunctional instrument in managing modern-day farming and environmental issues. Simultaneously, the bibliometric trends indicate that the further studies should proceed beyond the generalised statements of the advantages and pay more attention to the comparative field validation, soil-specific response mechanisms, nutrient interaction pathways and regionally specific application strategies. In this respect, the given study does not only trace the history and its current form of the field, but also indicates the next phase of development of the research in the area of biochar-based soil management.

Conclusion

The influence of biochar on soil nitrogen (N) dynamics indicates that no single formulation of biochar maximises mitigation simultaneously across the three N-loss pathways under all conditions. The potential of biochar as a sustainable soil amendment capable of enhancing N retention through adsorption of NH_4^+ , reducing NO_3^- leaching and NH_3 volatilisation along with alteration of the microbial habitats for optimising N transformations is also reflected in this study. The effectiveness of biochar is governed by several factors such as nature of feedstock, pyrolysis temperature, dosage of application, soil properties, interaction with fertiliser and management practices. Optimisation of biochar application can significantly reduce N_2O emission, improve soil fertility and improve crop productivity. The most protective combination emerging from this paper is: a wood- or straw-based feedstock, pyrolysed at low-to-moderate temperature, with near-neutral to moderately acidic pH, applied at a moderate rather than maximal rate and matched to acidic or fine-textured soils where the mitigation potential across all three pathways tends to converge most favourably. The alkaline or coarse-textured soil having high application rates are used for other agronomic reasons, practitioners should anticipate a trade-off likely gains in one pathway (e.g., N_2O suppression) at the cost of another

(e.g., increased NH_3 volatilisation). By integrating the insights from the bibliometric trends, this research highlights the potential of biochar in promoting sustainable N management and emphasises the need for long-term, site-specific field studies across varying agro-ecosystems to develop biochar management strategies that support agriculture under changing climate conditions. The bibliometric analysis of 1026 articles in the Scopus database that were published within the years 2017–26 demonstrates that the research on biochar on N dynamics in soil has proliferated at a fast rate and has become a well-organised and more interdisciplinary area of study. The results indicate that there is high increase in the number of publications, rise of central journals and major institutions and contribution of key authors and nations. According to thematic analysis, the field has developed, no longer the wide interest in soil improvement and C management but more specific themes such as the plot of N, microbial community, remediation and biological health of soil. The collaboration and citation networks also reveal that the biochar research has the firm intellectual ground but is still spreading to the new application-focused fields. Generally, the paper attests that biochar ceases to be a side issue but a significant field of research in the field of sustainable soil and agricultural sciences.

Future studies need to be conducted on long-term field validation beyond one growing season, soil-specific reactions, feedstock-influenced reactions, altered soil biodiversity as well as regionally tailored management practices to improve the implementation of biochar as a N management strategy in soils. Addressing these issues would allow the research field to move towards predicting application rate of biochar for sustainable N management.

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Authors' contributions

AS contributed to the literature search, thematic organisation, collection of data, synthesis, compilation of data and writing original draft preparation. BD contributed to the conceptualisation, critical review of literature, refinement of the overall manuscript, interpretation of results and supervision of the study. AKP contributed to the bibliometric analysis of this study. LPP contributed to the literature search and manuscript editing. SP contributed to preparation of figures and manuscript editing. VS contributed to data collection, literature screening and validation of bibliometric data. APM contributed to data curation, reference management and manuscript editing. KCS contributed to language editing and validation of concluding remarks. All the authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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