

Beyond Carbon: A Bibliometric and Thematic Analysis of Nitrogen Representation in Fertilizer Sustainability Research (1984–2026)

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Research Article

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Abstract

Global agricultural systems are under growing pressure to maintain food production while reducing environmental harm. Fertilizers sit at the center of this challenge: they're essential for crop productivity, yet they continue to raise sustainability concerns across several environmental dimensions. While much of the current discourse has focused on carbon emissions and climate change mitigation, nitrogen-related risks, including nitrate leaching, groundwater contamination, eutrophication, and nutrient-use inefficiency, remain significant and often overlooked. This study examines how prominently nitrogen-, carbon-, sustainability-, and policy-related concepts feature within the fertilizer sustainability literature. A dataset of 100 peer-reviewed publications spanning 1984 to 2026, sourced from **Scopus** and **Google Scholar** databases and retrieved from **ScienceDirect**, **MDPI**, **SpringerLink**, and **Wiley**, was analyzed using bibliometric and text-mining techniques, including keyword frequency analysis, dominance classification, co-occurrence network analysis, thematic mapping, and regression modeling. The results show 223 nitrogen-related mentions compared with just 43 carbon-related mentions, giving a nitrogen-to-carbon ratio of 5.19:1. Of the publications analyzed, 53 were nitrogen-dominant, 40 showed balanced attention to both themes, and only 7 were carbon-dominant. Food security, sustainability frameworks, carbon and climate, nitrogen leaching, nitrogen-use efficiency, and water quality emerged as the most prominent research themes. However, despite this strong focus on nitrogen, policy-related terminology appeared only 58 times across the dataset, and the relationship between nitrogen-related and policy-related terminology was weak ($R^2 = 0.053$). This suggests that scientific attention to nitrogen-related environmental challenges has not been matched by equivalent engagement with governance and policy responses. These findings point to a need for fertilizer sustainability frameworks that move beyond carbon-centered approaches and incorporate more robust nitrogen management and policy mechanisms.

1. Introduction

The challenge of producing enough food while keeping our environment healthy is a major question for agriculture today. Nitrogen is the number one nutrient that limits crop production throughout the world, and it is being applied to soils in the greatest quantities. However, the total efficiency of nitrogen that is applied to the soil is still below 70% (Malhi et al., 2001). Due to increased human activity (mainly from fertilizer production and burning fossil fuels), there is now more than twice the amount of reactive nitrogen in the environment than in previous years (De Vries et al., 2015). The presence of nitrous oxide has made it the third most important greenhouse gas and is the primary contributor to ozone layer depletion, which contributes to a greater risk of skin cancer and climate change-related health risks (De Vries, 2021). Only 11% of the world's land area is applied with nitrogen fertilizer yet nitrate levels in both surface water and groundwater have elevated with ammonia and nitrogen oxides from denitrification and soil volatilization still rising in the environment (Newbould, 1989). Too much nitrogen fertilizer has been found to directly increase nitrates present in both groundwaters and crops like root and leafy vegetables. There are also significant health issues associated with dietary exposure to nitrates such as cancers, neural tube defects in fetuses, diabetes and thyroid-related issues (Ahmed et al., 2017).

Rice, maize, and wheat provide a major source of food for the world. Although nitrogen is needed for a plant's growth, too much nitrogen can cause huge health and environmental issues. Therefore, nitrogen use efficiency has to be a key objective of sustainable cereal production (Zuluaga & Sonnante, 2019). Approximately 50%-75% of the nitrogen fertilizer (urea and nitrate: highly soluble in soil and water) applied in the intensive farming system is wasted and leached into the environment rather than being taken up by the plant (Hirel et al., 2011). Nitrate leaching accelerates exponentially once nitrogen inputs exceed crop demand so that the IPCC standard constant emission factor (30%) is severely underestimated in situations with significant nitrogen inputs (Wang et al., 2019).

Developed regions need stricter loss regulations, while developing nations need better access to balanced fertilizers for food security (Nieder & Benbi, 2022). According to Food and Agriculture Organization (FAO) projection, the total global usage of synthetic nitrogen fertilizer may increase by 50% between 2012 and 2050 which poses a challenge to the Paris Agreement's goal of limiting global temperature increases to 1.5–2°C (Menegat et al., 2022). Meanwhile, nitrogen pollution is expected to be 150% higher by 2050 than in 2010 and agriculture alone will drive 60% of that rise, making efficient nitrogen management difficult to handle (Martínez-Dalmau et al., 2021).

Nitrogen-related environmental concerns are discussed in the scientific literature, but modern sustainability discourse emphasizes more about carbon emissions and climate change mitigation. Between 1980 and 2020, nitrogen losses in China increased 2.3-fold and carbon emissions surged 6.5-fold, which highlights the need for integrated carbon and nitrogen management across human and natural subsystems (Xu et al., 2025). The Haber-Bosch process still dominates ammonia production for fertilizers, and even the push toward electrochemical alternatives is mostly framed around cutting energy use and carbon emissions. This once again demonstrates that fertilizer companies place the majority of their focus on carbon when it comes to sustainability, with far less of an emphasis on nitrate leaching (Kyriakou et al., 2020).

As carbon and nitrogen processes are closely connected with each other, strategies for decarbonization will also affect the nitrogen cycle in ways that are unlikely to be neutral. Therefore, research on the carbon-nitrogen co-benefit relationship is required rather than separately treating carbon and nitrogen issues (Zhang et al., 2024). In China, several agriculture support policies do not align well with goals of environmental sustainability; indirect support has more influence on farmers' production decisions compared to direct support (Wu et al., 2019). In India, fertilizer policies have reduced rural poverty, but the over-application of subsidized urea along with phosphorus and potassium fertilizers has resulted in nutrient inefficiencies, lower crop yields, and increased risk to the environment; for example, nitrous oxide emissions and nitrate leaching (Sapkota, 2025).

An example of a country that has taken significant steps to stop fertilizer overuse is China. In its Zero Increase Action Plan from 2015, China clearly commits to limiting the amount of fertilizer applied in accordance with environmental considerations and makes nitrogen use efficiency a primary focus of agricultural reform (Li et al., 2018). However, the current institutional framework for sustainable

development in China is inadequate to support the sustained rapid, transformational change through incrementalism that has characterized all other agricultural development efforts since the 1972 Stockholm Conference, according to Biermann et al. (2012).

The findings from this analysis point to a disconnect between what is published in the scientific literature regarding nitrogen and how nitrogen is represented in policy frameworks. To address this identified gap, a study of total 100 peer-reviewed research articles published between 1984 and 2026 is analysed utilizing bibliometric and text-mining methodologies. This analysis had four primary goals: (1) to quantify the number of occurrences of nitrogen-, carbon-, sustainability-, and policy-associated terminology throughout the existing fertilizer sustainability literature; (2) to identify the research themes that are most heavily researched within this field; (3) to examine the relationship between environmental concerns and policy-related discussions; and (4) to evaluate whether or not governance frameworks recognise the existing scientific understanding of nitrogen-related issues in the development of policies. All of these objectives are directed at examining the present state of sustainability research related to fertilizers and identifying some of the key gaps that exist between policy interest and scientific understanding about fertilizers.

2. Literature Review

2.1 Nitrogen-Related Environmental Risks: Nitrate Leaching, Groundwater Contamination, and Eutrophication

Nitrate leaching leads to a build-up of nitrate in soil as a result of excess water washing down the nitrate below ground level, influencing the increase of nitrate in water bodies around the world (Di & Cameron 2002, Wang et al. 2015) and accounts for the majority of global increases in concentrations, with 36% higher levels than in 1990 and about 60% of nitrate pollution coming from cropland; around 10 million people are exposed to excess nitrate in Europe (Nieder & Benbi 2022). Also, worldwide, approximately 19% of total fertilizer applied to land enters groundwater through leaching, with high-intensity agriculture receiving more than 20 kg/ha/year (Lin et al. 2001). This rapid increase in leaching occurs as soon as excess nitrate can no longer be taken up by the plant, so the 30% emission factor assigned to this aspect by the IPCC is probably an understatement of the actual extent of this problem (Wang et al. 2019). Deep nitrate leaching and declining groundwater levels from excessive irrigation are examples of nitrate leaching in the North China Plain (Li et al. 2026); while from better irrigation and fertigation management in Nebraska decreased nitrate leaching without negatively affecting yields (Spalding et al. 2001).

Different types of soil may allow for various amounts of leaching depending on how much they drain out into the environment; sandy soils drain out fast by leaching more than clay rich and loam soils, which have less drainage. The rate of leaching on agricultural land typically increases as nitrogen input levels increase because nitrogen levels are typically the highest in or near non-productive areas of the land, especially for low productivity crops like fall-sown loamy sand soils, which have higher nitrate concentrations than EU standards for drinking-water quality after applying manure (Van Es et al., 2006).

The contribution of arable and horticultural crop production to leaching is substantial by land area, due to cost-effective use of fertilizer on productive land (Goulding, 2000). Grazing grasslands tend to leach out approximately 5.6 times more nitrates than cut grasslands, thereby negating the argument that grasslands do not pose a leaching risk (Ryden et al., 1984). Approximately 81% of all nitrogen entering into watercourses and around 70% of all nitrogen reaching marine environments in Denmark comes from agriculture and has not improved since implementation of environmental policy (Hansen et al., 2000).

Besides affecting water systems, the leaching of nitrates is a leading driver of everything from algal blooms to eutrophication, as well as de-stabilised biodiversity, and presents human health risks such as methaemoglobinaemia (blue baby syndrome) and certain cancers (De Vries, 2021; Nieder & Benbi, 2022; Hina, 2024). Additionally, the over-fertilisation of vegetables has been linked to hypothyroidism, neural tube defects and diabetes (Ahmed et al., 2017). Evidence of a positive correlation between diet and harm from nitrates is ambiguous; however, ecological damage from nitrates is unambiguously confirmed (Newbould, 1989).

2.2 Nitrogen Use Efficiency (NUE)

Globally, nitrogen use efficiency for cereal production averages approximately 33%, resulting in a total loss of estimated value of \$15.9 billion/year related to fertilizer. The nitrogen use efficiency for cereal production globally in 2015 was approximately 35% (41% in US, 30% in China, and just under 21% in India) reflecting virtually no increased efficiency since 2002 (Omara et al., 2019). Additionally, nitrogen use efficiency decreases proportionally (Johnson & Raun, 2003) with increasing application rates, as no one management practice has been proven adequate to address this issue (Sharma & Bali, 2017). In addition, in intensive agricultural practice, 50–75% of applied nitrogen is lost to the environment (Hirel et al., 2011). Due to the nitrogen budget in India transitioning from a net deficit to a net surplus, nitrogen use efficiency for agricultural production has decreased (Velayudhan et al., 2024). Vegetables produced in greenhouse environments exhibit very poor nitrogen use efficiency (15–35%) and large residual leaching due to history of over-fertilization (Qasim et al., 2021).

Inadequate NUE is typically due to the repetition of the fertilizer application periods versus the actual need of the plants for that fertilizer (Sharma & Bali 2018). Nitrogen can be lost regardless of its source due to various mechanisms such as volatility, immobilization, denitrification and leaching based on the soil type, climate and production management system in which it was applied (Malhi et al. 2001 and Raun & Johnson 1999). NUE includes both the overall efficiency of nutrient uptake/utilization; therefore, both factors need to be improved to achieve optimum crop yields while using less input (Lea & Azevedo 2006). In the future, a greater understanding of the genetic basis of nitrogen uptake and recycling in crops has the potential to significantly enhance NUE (Zuluaga & Sonnante 2019 ; Lea & Azevedo 2006).

GreenSeeker, drones, and satellites have proven to be much better than traditional methods of testing soils (Sharma & Bali, 2017). Other methods that show promise are breeding, molecular genetics and the use of cover crops (Hirel et al., 2011). Yield-based nitrogen algorithms for corn are unable to give reliable results when producing corn, so there is much interest in the use of alternative methods that require

more data (Rodriguez et al., 2019). Use of site-specific management can decrease nitrogen that you use without decreasing yield (Lobell, 2007); in China, this type of management has resulted in a 32% decrease in fertilizer needed to produce the same amount of rice while increasing yield 5% (Peng et al., 2010). The most effective nitrogen treatments for rice and oilseeds in rotation provided a nitrogen use efficiency (NUE) of 38.5% (Yousaf et al., 2016), but using a super-hybrid rice variety and splitting the nitrogen application into 4 applications totaling 202.15 kg N / ha produced both maximum yield and NUE (He et al., 2024). When optimising the amount of nitrogen used along with practices such as irrigation, tillage, livestock manure application and straw return, yield improved 5.4% while NUE improved by 55% (Liu et al., 2024).

2.3 Carbon, Climate Change, and N₂O Emissions

Agriculture is the primary source of emissions of carbon dioxide (CO₂), nitrous oxide (N₂O), and methane, all of which contribute to global warming (Liu et al., 2019). This sector produces approximately 58% of non-CO₂ anthropogenic greenhouse gas emissions and contributes 14% of total greenhouse gas emission (Beach et al., 2008). Additionally, agricultural intensification and land use change have increased the amount of greenhouse gases derived from soils, with both methane and N₂O having much higher warming potential than their physical mass (Chataut et al., 2023). Nevertheless, agriculture also has significant potential to mitigate climate change through sustainable practices, better management of livestock, and precision agriculture; however, many smallholder farmers face barriers to adopting those practices (Kamyab et al., 2024). Farmland contributes to 10–12% of global greenhouse gas emissions, with nitrogen fertilizer responsible for 60% of N₂O emissions and the associated depletion of stratospheric ozone (Guo et al., 2022; Buckingham et al., 2014).

N₂O forms as a result of the nitrification and denitrification processes (Byrnes, 1990). Cultivated land emitted N₂O at an annual rate of 3.5 Tg by the 1990s (1.5 Tg from synthetic fertilizers alone), representing a 150% increase from 1970 levels (Smith et al., 1997). Since the warming potential of N₂O is approximately 265 times that of CO₂, reducing nitrogen inputs is a key mechanism for mitigating climate change (Menegat et al., 2022). However, many emissions inventories continue to utilize approximate and oversimplified IPCC Tier 1 methods (Buckingham et al., 2014) and indirect leaching pathways have not been regulated (Smith et al., 1997). In the UK, ammonium nitrate was found to produce greater quantities of N₂O than urea; by contrast, using inhibitors to treat urea reduced nitrogen oxide emissions by as much as 96% (Dobbie & Smith, 2003). Similar results were found in Australian sugarcane production systems, where exponential increases in N₂O emissions were reported with increasing nitrogen rates and waterlogging (Takeda et al., 2021); in South African agricultural systems, emissions of 7.3 million tons of CO₂e occurred in 2018, a legacy from the fertilizer subsidy programs of the 1950s (Tongwane et al., 2020).

According to projections made by the Food and Agriculture Organisation (FAO), the world will use 50% more synthesised nitrogen by the year 2050, posing a major threat to the targets of the Paris Agreement (Menegat et al., 2022). For example, between 1980 and 2020, nitrogen losses and carbon emissions in China grew 2.3 times and 6.5 times respectively, indicating that both should be managed alongside each

other (Xu et al., 2025). The profound interconnection of decarbonisation and nitrogen cycles reinforces the argument that they must be managed together (Zhang et al., 2024). There may also be opportunities to apply lessons learned in managing carbon to nitrogen policy, such as the establishment of stabilization targets and cap and trade systems (Socolow, 1999). Through multi-omics research in maize, scientists are beginning to identify genes and metabolites that control the allocation of carbon and nitrogen in plants (Yao et al., 2026). Meanwhile, developing countries contribute about 60% of the world's greenhouse gas emissions and 74% of agricultural greenhouse gas emissions, but have been largely excluded from international policy frameworks (Maraseni and Qu, 2016).

2.4 Fertilizer Management Practices

Reducing nitrogen application from 360 kg/ha (a farming common application rate) to 180 kg/ha resulted in maintenance of vegetable crop yield but a reduction in N₂O emissions by about 60% (Xu et al., 2017). In contrast, excessive amounts applied to crops resulted in increased nitrate leaching rates of nearly 64% (Zotarelli et al., 2007). This highlights the adverse effects of over applying fertilizer on both the environment and yield, which has resulted in calls for methods based on the 4Rs: Using the right source, rate, time and place (Penuelas et al, 2023). The high percentage of farmers (70%) in Bangladesh who use only broadcasting as their primary method of fertilizer application illustrates the need for additional placement options of fertilizer and crop chemicals (Rahman and Zhang, 2018).

Increased cover crop utilization has been shown to result in significantly decreased nitrate (NO₃⁻) leaching with a 69% reduction to the leaching of NO₃⁻ from the fallow system (Nouri et al., 2022). Brassicaceae and Poaceae cover crops (e.g., turnips and ryegrass) have produced the greatest reduction in leaching (Nouri et al., 2022). Similarly, catch crops reduced leaching of N by 20–23 kg N/ha independent of the farming system used (De Notaris et al., 2018), and the species of cover crop appears to be more important than the source of N (McCracken et al., 1994). The use of irrigation based on crop demand has produced similar results with reductions in leaching of N by 80% while using improved fertilizer management decreased leaching by 40% and cover crops decreased leaching by 50% (Quemada et al., 2013).

Controlled release urea increased potato yields 49.8% while also decreasing nitrate leaching (Tian et al., 2018) and improving NUE by 30–44% across rice systems (Lyu et al., 2021). However, the use of inhibitors or splitting application did not show any measurable benefits in tropical maize (Lucas et al., 2019), although the NBPT shows promise where no-till is used (Malhi et al., 2001). In applying biochar to reduce N₂O emissions by 38%, and also to reduce leaching by 13% (Borchard et al., 2019), and using organic substitution reduced both leaching and runoff by more than 30% (Wei et al., 2021; Hina, 2024). Bio-gypsum demonstrated good results in increasing nitrogen uptake by 78% and yield by 28% (Ahmed et al., 2025). Life Cycle Assessments (LCA) supports the argument for optimising the selection of fertilisers (Hasler et al., 2015; El Chami et al., 2023), Commonly irrigation practices co-determine carbon, nitrogen, and overall emissions (Zhou et al., 2026).

2.5 Policy and Governance Frameworks

Since the 1972 Stockholm Conference, institutional sustainability frameworks have not been able to produce significant transformative change (Biermann et al. 2012). The scholarship of environmental governance has taken on various conceptual perspectives through the years; however, translating that scholarship into effective policy implementation continues to be a major challenge (Davidson & Frickel, 2004). In the case of China, the agricultural subsidies provided do not sufficiently support the goal of sustainability (Wu et al. 2019). This has led to underpricing fertilizers historically; resulting in their over application and subsequent pollution from the over application of fertilizers used (Li et al. 2013). However, the 2015 Zero Increase Action Plan seeks a pathway through using more effective fertilizers and inhibitors to achieve better nitrogen use efficiency (NUE) (Li et al. 2018). In India, urea subsidies also create an imbalance among nutrients applied and increase the potential for N₂O emissions (Sapkota 2025), and trend toward increasing emissions of ammonia (Móring et al. 2021).

The European Union (EU) Green Deal aims to reduce nitrogen leaching by 50% by 2030 (De Vries 2021), with the EU Emission Trading System specifically targeting N₂O emissions emitted from nitric acid manufacturing plants (Pérez-Ramírez 2005). In Australia, over AUD \$20 million have been expended on N₂O research programs (Laing et al. 2023). Although there are several examples of commitments by nations or regions to reduce N₂O emissions, indirect pathways for leaching through groundwater remain globally inadequately regulated (Smith et al. 1997). Further, the differences between developed and developing countries have caused a need for geographically specific solutions to produce a balance between their varying sets of needs (Nieder & Benbi 2022).

Farmers in Germany are interested in climate-friendly labels and incentives; however, many do not have sufficient knowledge on how to move forward with these types of programs (Jantke et al., 2020; Martínez-Dalmau et al., 2021). Short-term uptake of organic fertilizer (via subsidies) has been supported; yet, long-term sustainability will require behavioral and digital reinforcement (Liao et al., 2025). More generally, farmers are responsive to incentives than to regulatory mechanisms (Wu & Ge, 2019). Sustainable intensification efforts have been aided by both subsidy and safety-net programs in Sub-Saharan Africa (Holden, 2018). In Rwanda, the rapid increase in fertilizer prices caused by COVID-19 has made the use of real-time data systems essential for informing subsidy reform efforts at the time of a crisis (Spielman et al., 2025).

2.6 Sustainability Frameworks and Application to Fertilizer Research

Depending on the situation, context, size, and viewpoint, people tend to define sustainability differently (Brown et al., 1987), which indicates that a decision-making framework for sustainability should be integrated with sustainability (Chofreh & Goni, 2017) and the primary objective of meeting human needs should be achieved simultaneously with ecological resilience (Rockström et al., 2017). Within food systems, how the environment is defined impacts crisis response; for example, food sovereignty delineates boundaries in the governance of agricultural sustainability (McMichael, 2011). However, established frameworks continue to receive criticism for multiple reasons: they provide no or limited

coverage of resilience (Roostaie et al., 2021), lack focus on positive peace (Candelaria et al., 2023), provide unbalanced weightings for indicators (Paulvannan Kanmani et al., 2020), and there is limited knowledge of socio-ecological feedback loops (Mastrángelo et al., 2019). Nonetheless, multi-disciplinary, integrated approaches based on the SDG pillars have been identified as potential solutions to addressing the identified gaps (Opon & Henry, 2019; Taelman et al., 2020).

Although the Haber-Bosch process continues to dominate global agriculture, fertilizer sustainability initiatives have focused primarily on carbon, leaving nitrogen leaching to go unaddressed. The need for nexus-approaches will address multiple sectors of society. Achieving integrated carbon-nitrogen management would potentially result in reducing nitrogen losses by 74% and reducing carbon emissions by 91% by the year 2060, providing approximately \$1384 billion to the society in total net benefits. Approaches such as these are able to utilize transferable lessons from carbon management as well as irrigation nexus strategies. More generally, there are numerous sustainability tools that can provide context for fertilizer research, including: multi-regional input-output (MRIO) databases (Wood et al., 2014), energy strategy analysis reports (Chen et al., 2020), resource-based business frameworks (Dao et al., 2011), investor-oriented reporting standards (Carungu et al., 2026), informal institutional methods (Song, 2020), and assessments of virtual water trade in which it was found that approximately 68.3% of the total wheat trade is unsustainable (Hekmatnia et al., 2023). Collectively, these sustainable tools provide context for the environment within which fertilizer research must take place.

3. Methodology

3.1 Data Collection

A literature review was performed using both Scopus and Google Scholar to find peer-reviewed research articles regarding the sustainability of fertilizers with a strong focus on environmental issues related to nitrogen, carbon and climate issues, sustainability frameworks and policy/governance discussions. The search included various combinations of the terms, 'nitrogen fertilizer', 'nitrate leaching', 'nitrogen use efficiency', 'fertilizer sustainability', 'carbon emissions from agriculture', 'fertilizer policy' as well as other related terms and themes of interest in this review

Approximately 250 potential publications were initially sourced from ScienceDirect, MDPI, SpringerLink, Wiley and other sources and screened for their relevance to the nitrogen-carbon-policy framework that this review was based upon. Publications were excluded from analysis if they did not clearly address fertilizer-related nitrogen, carbon or sustainability or policy issues

A total of 100 publications from 1984 to 2026 were contained in the final dataset of selected literature. The intent was to select literature that would provide comprehensive coverage of the study period and represent major topic areas (e.g., nitrogen leaching, nitrogen use efficiency, N₂O emissions, carbon and climate, public policy and governance, and food security) examined in this study.

3.2 Data Preparation

The title and abstract of each document were used to create one data record that contains relevant terms from both sections. In addition, the year of publication has been recorded for a time-based analysis as well. All publications have been reviewed during the screening and selection process, but only the above three fields were taken for the analysis because the intent of the research is to determine how strongly the terms nitrogen, carbon, sustainability, and policy are represented in fertilizer sustainability literature. Since abstracts generally reflect the central focus and thematic emphasis of the publication, they provide an adequate basis for determining if it emphasizes nitrogen or carbon discourse and also measure how much a publication discusses policy-related language.

3.3 Keyword Frequency Analysis

A keyword frequency analysis was done by using whole-word matching to calculate the combined text record of all of the publications and then categorizing based on 4 different categories of keywords (carbon-related terminology, nitrogen-related terminology, policy-related terminology or sustainability-related terminology). Also, whole-word matching was done to only count exact and complete instances of keywords so as to exclude partial or incomplete matches (e.g., a search term appearing as part of a longer and completely different word). The total frequency of occurrence of the categories was calculated based on the overall dataset, which allowed for an overall determination of the relative prominence of each theme in the literature.

3.4 Dominance Classification

In order to classify each publication as either nitrogen-dominant, carbon-dominant, or equally emphasised, carbon- and nitrogen-related terminology was categorised based on its relative frequency of occurrence. Specifically, for each publication, the number of nitrogen-related terms was compared to the number of carbon-related terms, thus allowing for the analysis of overall frequency results in more depth than just by aggregating publications together.

3.5 Regression Analysis

To determine how environmental terms are used in relation to policy discourse at the level of each publication, linear regression analysis was conducted. This study tested two relationships: (1) the relationship between terms related to nitrogen and those related to policy; and (2) the relationship between terms related to carbon and those related to policy. Coefficient of determination (R^2), p-value, and regression slope were used to assess the strength of association between each term pair. The significance of each term pair's association was determined via p-values.

3.6 Co-occurrence Network Analysis

A keyword co-occurrence network was built using the literature to analyze the patterns of links between publications in terms of thematic connectivity. The network contains terms that describe nitrogen management, carbon and climate, policy and governance, and agronomy practices. These terms were identified from the combined text record for each publication. A connection was documented between two terms whenever they occurred together within the same publication. The node size indicates how

frequently each term appears overall and edge thickness shows how frequently each term pair occurred, giving an overall view of the relationships between thematic areas.

3.7 Thematic Mapping

Ten thematic areas were created from the analysis of recurring ideas throughout the dataset: Nitrogen leaching, Nitrous oxide (N₂O) emissions, Nitrogen use efficiency (NUE) advancements, Policy/governance, Carbon and Climate Change, Precision Agriculture, Organic Agriculture, Sustainability framework, Food Security, and Water Quality. Centrality (the measure of how closely associated successive themes are against other themes in the scientific literature) and density (the measure of how well-developed the terms associated with a theme are) were determined for each theme to evaluate their relative importance and development stage across all research activities.

4. Results

The number of nitrogen references in the 100 publications analysed (1984–2026) was about 5.19 times larger than the total number of carbon references. For example, nitrogen references were recorded 223 times, while carbon references were recorded 43 times. Therefore, the nitrogen:carbon ratio is 5.19:1. The third most frequently recorded reference category in this report is the policy category with 58 occurrences, while the sustainability reference category occurred 170 times (Fig. 3A).

The classification of the literature was based on their dominant theme, nitrogen (53 papers), carbon (7 papers), and equal attention to both nitrogen and carbon (40 papers) as measured in Fig. 3D. Over the timescale of the study, we find an increased number of nitrogen (dominant) and equal attention (to both nitrogen and carbon) papers emerging since approximately 2018 while observing very few (carbon) papers were published throughout the entire timeframe.

According to the publication trend (Fig. 1A), there has been a gradual and stable increase in research within this field from the 1980s until around 2010, whereupon there has been a dramatic rise in publications since that time, with an increase in the number of publications peaking at 12 in a single year from 2018–2019. Figure 1B shows that mentions of nitrogen generally exceed those of carbon during most of the time frame with nitrogen exhibiting multiple peaks - notably around 2000 and again after 2018 - while mention of carbon remains consistently low (with only a small increase seen in the last few years).

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As shown in Keyword co-occurrence network (Fig. 2), "nitrogen" and "nitrate" are the 2 largest nodes in this network; they are the most central to many other agronomic keywords (such as fertiliser, leaching, urea, yield, and efficiency), as well as several sustainability- and policy-related keywords. Carbon keywords (such as emissions, climate, greenhouse, and dioxide) are clustered together and are less centrally clustered in the network than nitrogen-related keywords are. "Sustainability" and "framework"

are at the boundary position between these clusters, serving as connectors linking agronomic literature focused primarily on nitrogen and the smaller cluster of carbon and climate keywords.

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Regression analysis (shown in Figs. 3B and 3C) shows a weak yet significant negative correlation between nitrogen mentions and policy mentions ($R^2 = 0.053$, $p = 0.0210$, slope = -0.1042), suggesting that as nitrogen mention counts increase, so do the number of papers with lower counts of policy mentions. In contrast, the relationship between carbon and policy mentions was not statistically significant ($R^2 = 0.003$, $p = 0.5681$; slope = -0.0642), suggesting there is no meaningful correlation between attention to carbon and attention to policy based on this data set.

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The thematic map (Fig. 4) shows the position of the 10 different themes that were identified. Food Security had the highest centrality score (0.60) and also had the highest number of publications and, therefore, was near to the boundary of the motor-theme segment as compared to other themes. The Sustainability Framework (0.43 centrality and 0.47 density) was placed close to central with respect to other themes. Nitrogen Leaching had the highest density of all themes (0.75) and moderate centrality (0.36) and was therefore placed inside of the niche-theme segment. N₂O Emissions (0.28 centrality, 0.61 density) and NUE Improvement (0.33 centrality, 0.52 density) are very similar in terms of both characteristics. Carbon & Climate (0.40 centrality, 0.35 density) were placed vertically between the basic and emerging-theme segments just below the density midpoint. Policy & Governance (0.20 centrality, 0.30 density), Organic Farming (0.30 centrality, 0.17 density), Water Quality (0.27 centrality, 0.19 density), and Precision Agriculture (0.06 centrality, 0.17 density) were placed within the emerging or declining segment and had low values for both characteristics.

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5. Discussion

5.1 The Nitrogen-Carbon Imbalance

The descriptive statistics reveal a clear disparity in the representation of nitrogen and carbon terms in the dataset. Nitrogen terms were found 223 times while carbon terms only appeared 43 times giving a ratio of 5.19:1. This disparity is shown in the dominance classifications where 53 publications were classified as nitrogen dominant and only 7 as carbon dominant. There were also 40 publications classified as equally emphasizing nitrogen and carbon. The findings suggest that nitrogen-related issues have been given a far greater proportion of scholarly attention than carbon-related issues, despite the fact that carbon and climate are frequently used as frames within wider sustainability literature. This is consistent with previous characterizations of nitrogen's broad environmental impact, including its

contribution to eutrophication, groundwater pollution, and greenhouse gas emissions (Nieder & Benbi, 2022; De Vries, 2021).

5.2 The Relationship Between Nitrogen, Carbon, and Policy Discourse

According to regression analysis results, there was a statistically significant but weak negative association between use of nitrogen terminology ($R^2 = 0.053$, $p = 0.0210$, slope = -0.1042) as compared to use of policy terminology. Conversely, for carbon terminology compared to policy terminology, the association was not statistically significant ($R^2 = 0.003$, $p = 0.5681$; slope = -0.0642). These results indicate that a publication that uses more nitrogen-related terminology is not likely to have more policy-related terminology, and in fact, will likely have slightly less. This suggests that there exists separation between scientific literature which has a focus on addressing environmental problems related to nitrogen from the literature that has a focus on addressing policy responses to those environmental problems. Earlier studies have noted this same level of separation between scientific evidence and policy implementation; more specifically, researchers noted that many geographical regions are not incorporated into Agricultural Emission Policy frameworks (Maraseni & Qu, 2016), and that farmers respond to information and economic incentives to a greater extent than they do to regulatory measures (Jantke et al., 2020; Wu & Ge, 2019).

5.3 Thematic Development Patterns

The thematic analysis offers additional clarity to these findings. The highest count was Food Security (60 papers), followed by Sustainability Framework (43 papers) and Carbon and Climate (40 papers). The remaining nitrogen-related themes were Nitrogen Leaching (36 papers), NUE Improvement (33 papers), and N_2O Emissions (28 papers). These papers represent large numbers of separate instances across multiple sub-themes, indicating that the nitrogen-related issues are dispersed across multiple sub-themes rather than all together in one sub-theme. The Policy and Governance was 20 papers, second-lowest number of papers after Precision Agriculture (6).

This distribution implies that nitrogen-related research included within the dataset cover a variety of focused areas such as leaching, emissions and use-efficiency each area representing an established range of scholarly work on their own merits (Di & Cameron, 2002; Wang et al., 2019; Nouri & al., 2022; Quemada & al., 2013; Hirel & al., 2011; Raun & Johnson, 1999; Omara & al., 2019). However, the comparably small volume of Policy and Governance shows that while nitrogen research focused on those subjects has received its scholarly contribution from earlier studies, there has not been a related proportionate volume of literature dealing with policy-based literature on nitrogen within this same dataset.

Carbon and Climate has the third largest representation in the themes of the dataset (40 papers) despite having a relatively small number of occurrences of carbon terminology (43 in total), indicating that there are a moderate number of papers addressing carbon and climate themes but they are of relatively low

intensity in the context of each individual piece of published research. This might mean that carbon and climate topics are often mentioned in a secondary or contextual sense rather than as a primary theme, which relates to recent calls for greater integration of carbon and nitrogen cycles in sustainability research (Xu et al., 2025; Zhang et al., 2024).

5.4 Co-occurrence Patterns

The co-occurrence analysis of the network confirms these findings. Nitrogen-centric vocabulary represented the densest cluster in the network greatly interconnected to concepts that had to do with fertilizer efficiency, water quality, and food production. Policy terminology that had connections to environmental or agronomy themes was less prominent than terms that were technical in nature or environmental so this supports the regression findings and the lesser presence of the Policy and Governance theme and reinforces the conclusion that the discussion surrounding issues of policy and governance were more marginal within this network of concepts.

5.5 Limitations

The data sample consists of 100 publications, and each reference to a publication/the related topic has been recorded using a keyword-based frequency approach; this method is transparent and reproducible. However, the keyword approach lacks ability to reflect the contextual meaning of how the terminology was used within each of the references.

Furthermore, while developing the sample, the sample was acquired with a focus on fertilizer/nitrogen-based literature; therefore, this focus may be reflected by the relative similitude of frequency observations between nitrogen related articles as opposed to policy related articles. The consistency of descriptive statistics, regression results, thematic analysis and co-occurrence networks found in this dataset demonstrate that there is indeed evidence of a differentiation in nitrogen related articles as compared to policy related articles throughout the sample.

Thus, it can be concluded that the difference in nitrogen and policy related articles is a accurate representation rather than an artifact of a single methodological approach.

6. Conclusion

The study looked at nitrogen, carbon, and policy-related terms from 100 published articles in the peer reviewed literature about fertilizer sustainability from 1984 to 2026. There was a much greater frequency of the nitrogen term compared to a carbon term (5.19 vs. 1). Likewise, more than 50% of the papers were classified as being nitrogen dominant. Policy terms appeared less than nitrogen and carbon terms (monotonic regression found a weak, statistically significant negative relationship between nitrogen and policy term usage but found no significant relationship between carbon and policy terms). The thematic map and co-occurrence network show that in terms of nitrogen type terms, multiple well-defined sub-themes concerning nitrogen existed (e.g., nitrogen leaching, NUE improvements, and N₂O emissions), while Policy and Governance were among the lowest represented themes for nitrogen-related terms.

Carbon and Climate were relatively moderate representations for thematically represented, despite relatively low usage overall of carbon-related terminology.

The evidence reviewed indicates that nitrogen is a major component of fertilizer sustainability literature. In many regards, there appears to be more representation of nitrogen issues than that of carbon issues; however, nitrogen has been inadequately represented in regard to policy terminology in both instances, therefore there is a disparity between the scientific literature on nitrogen environmental concerns and the literature on corresponding policy responses. Additional studies that incorporate larger and/or more diverse datasets, with more refined keyword categorization, and a temporal analysis of policy terminology relative to nitrogen findings and other related content, will allow for determining whether the observed gap in the literature as described in this research is indicative of the entire literature or specific to the dataset evaluated in this research.

Declarations

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Author Contribution

P.V was responsible for the full scope of this research, including conceptualization, data collection, methodology, formal analysis, investigation, visualization, figure, table and writing of the original draft, review, and editing.

Data Availability

Data can be provided upon request.

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Figures

Figure 1: Publication Trends and Research Focus (1984-2026)

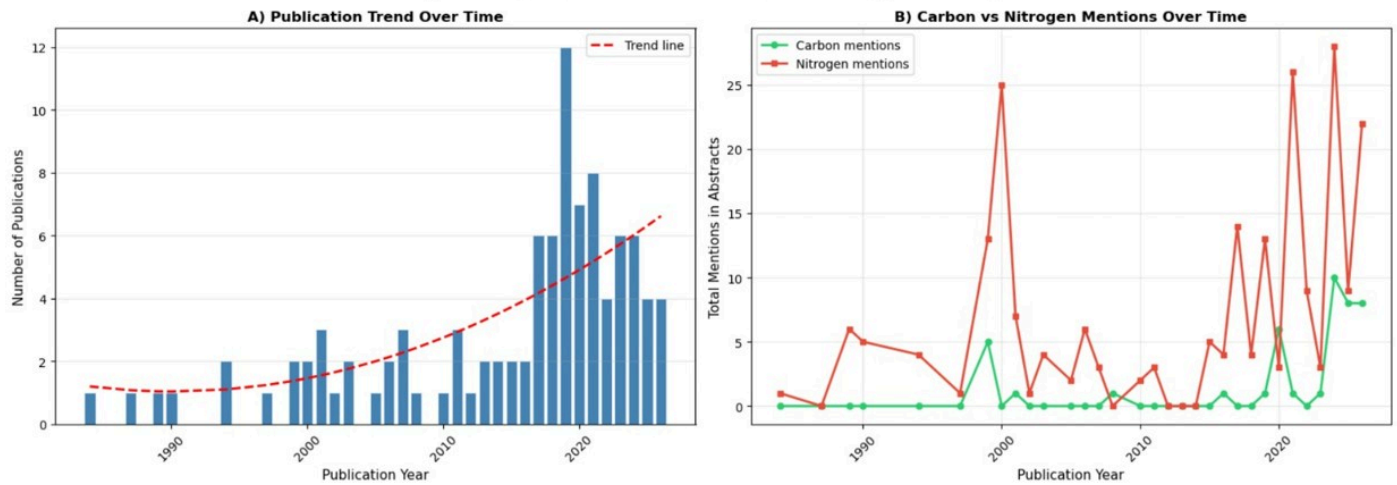


Figure 1

Publication trends and research focus (1984–2026). A Publication trend over time. B Carbon vs nitrogen mentions over time.

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Figure 2: Keyword Co-occurrence Network
(Node size = frequency; Edge thickness = co-occurrence strength)

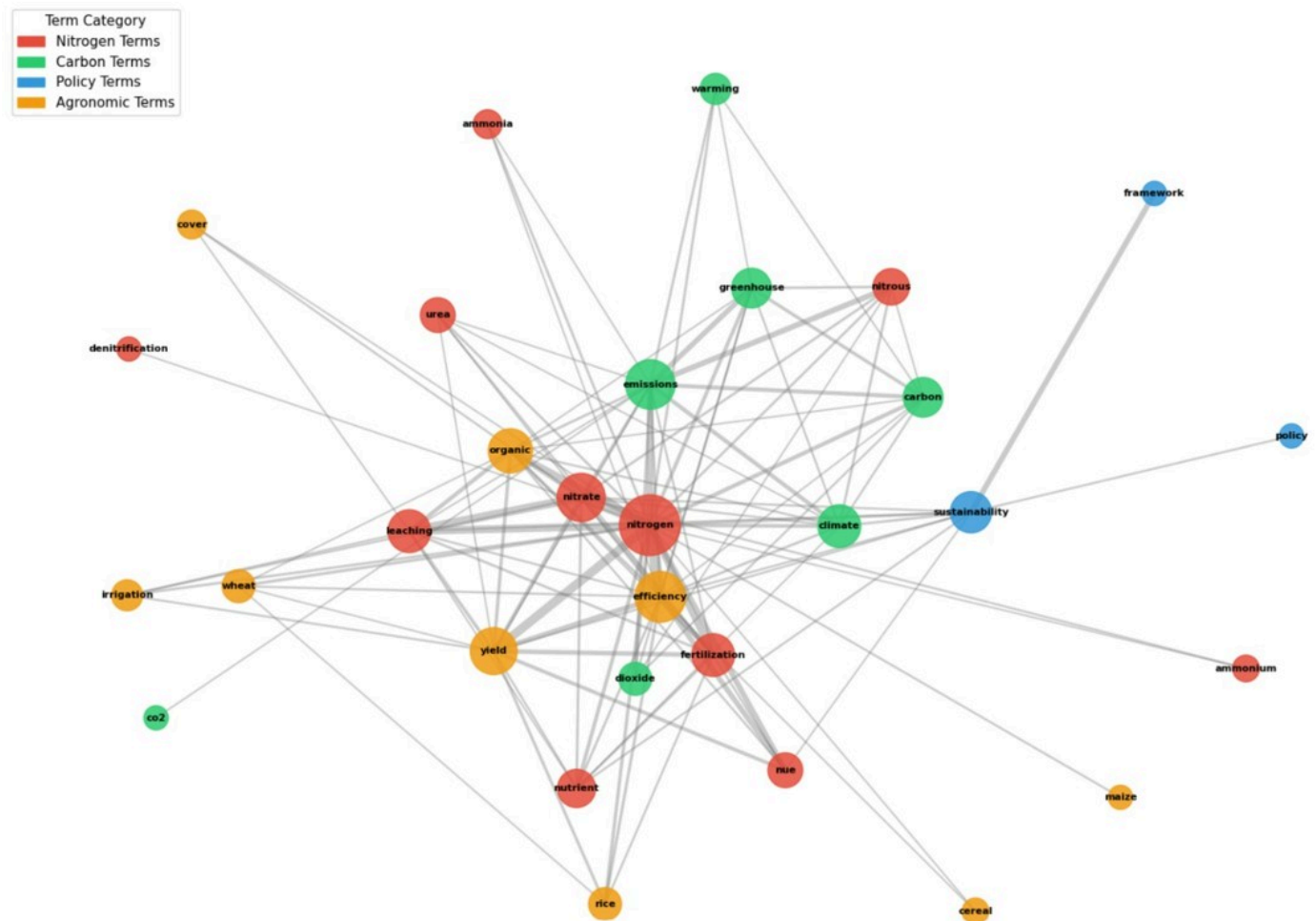


Figure 2

Keyword co-occurrence network. Node size represents term frequency; edge thickness represents co-occurrence strength between terms.

Made by author

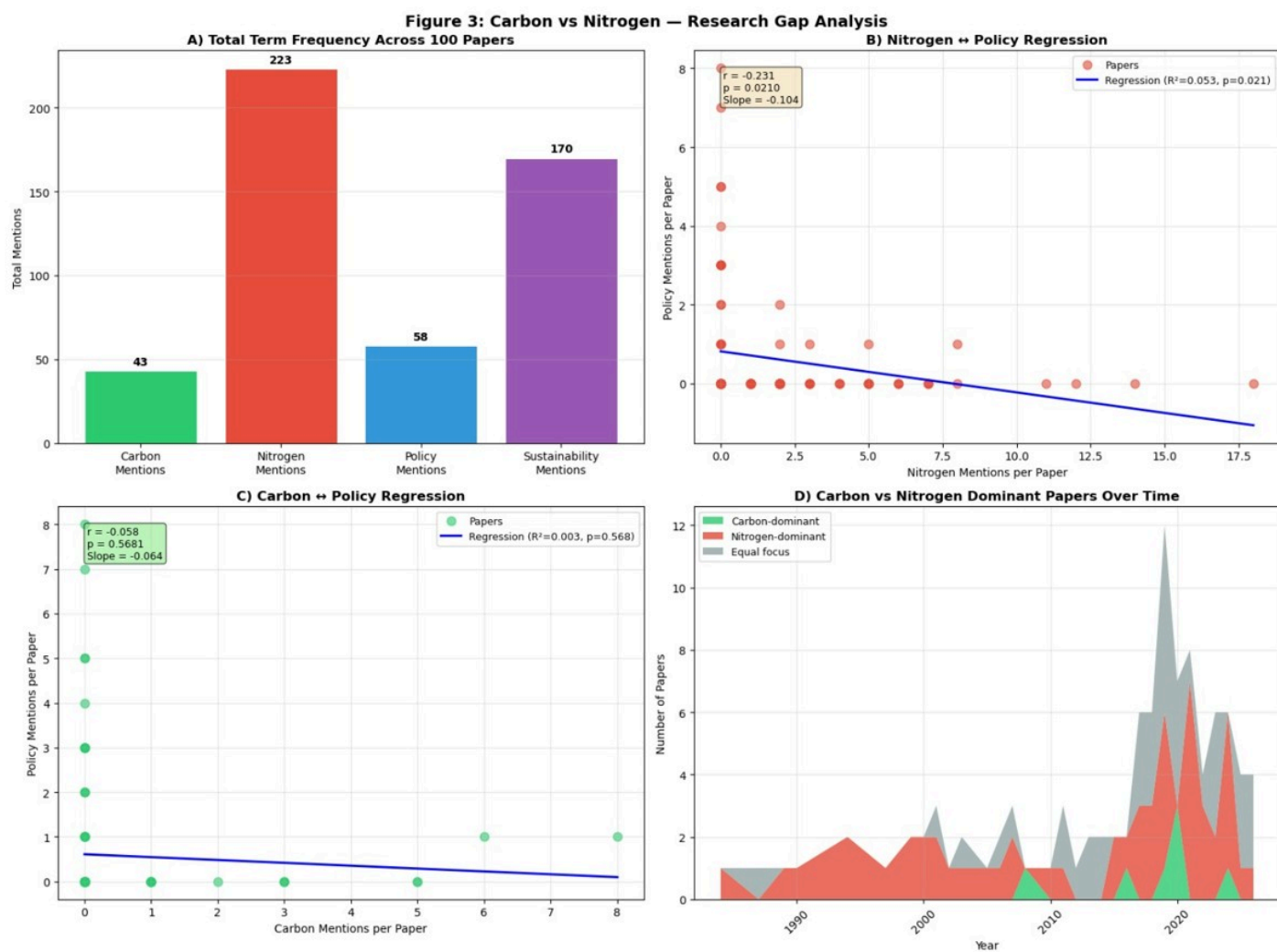


Figure 3

Carbon vs nitrogen research gap analysis. A Total term frequency across 100 papers. B Nitrogen–policy regression. C Carbon–policy regression. D Carbon vs nitrogen dominant papers over time.

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Figure 4: Thematic Map — Research Landscape of Nitrogen Fertilizer Literature
(Bubble size = number of papers)

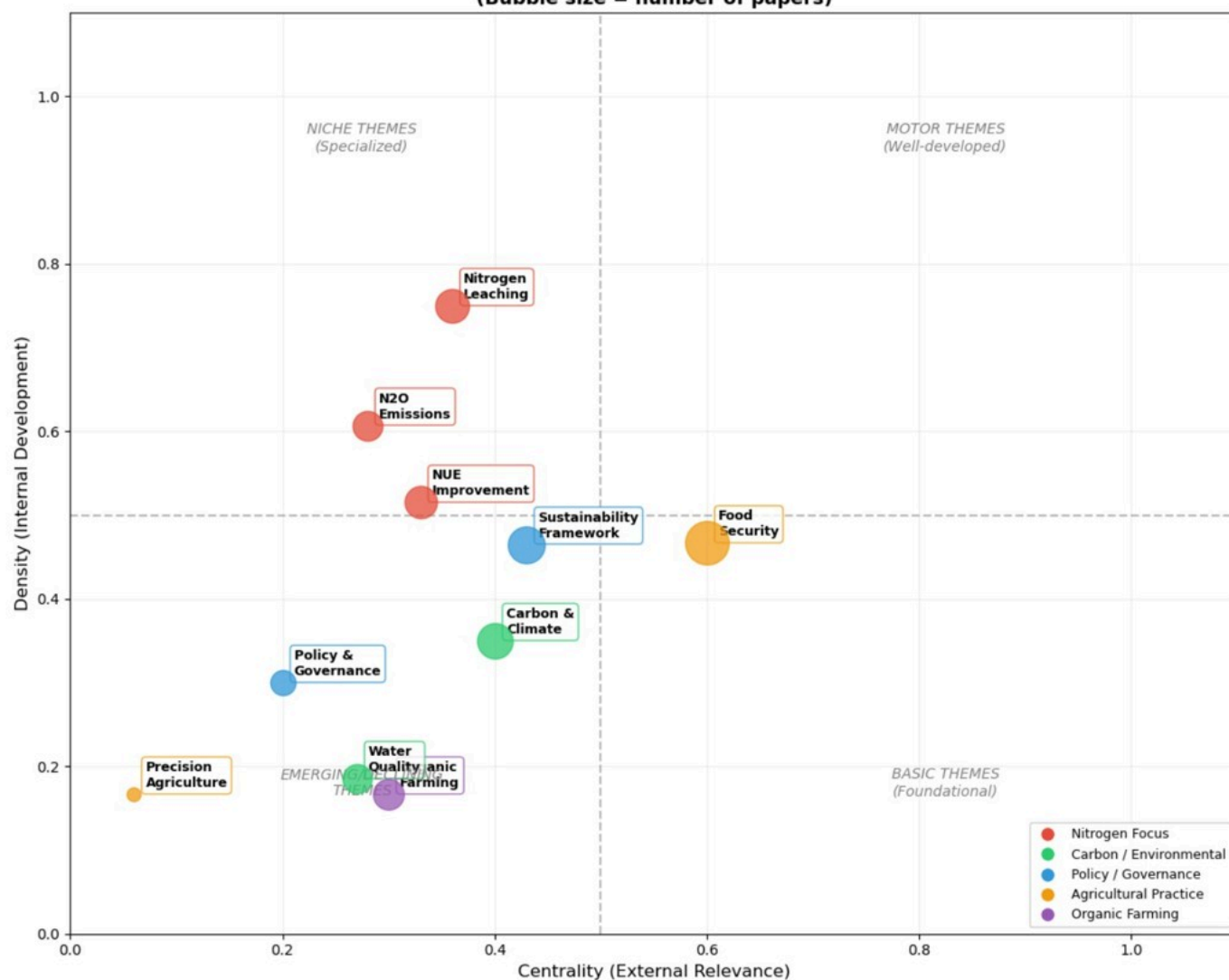


Figure 4

Thematic map of the research landscape of nitrogen fertilizer literature. Bubble size represents number of papers; dashed lines divide the four quadrants (motor, niche, basic, and emerging/declining themes).

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