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The manuscript by Mendoza-Carreón *et al.* has been retracted at the request of the authors due to the cessation of the journal *Soil Health*.

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Review

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# Importance and inconsistencies of the influence of soil properties on nitrogen mineralization: a systematic review

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## Abstract

Climate and soil properties profoundly impact N mineralization ( $N_{min}$ ). Hence, there is a critical need to identify how physical-chemical-biological factors involved in organic matter decomposition influence globally reported predictive models. This paper reflects research focused on those factors considered relevant and used during the construction of  $N_{min}$  models. The literature data found on factors affecting  $N_{min}$  or N availability in soils published since 1990 was downloaded to a database in Access. Using different bivariate and multivariate statistical techniques, we compiled results of 785 statistical analyses presented by authors of 90 research articles that related  $N_{min}$  and environmental factors, management strategies, and soil biological and physicochemical attributes. For organization purposes, we decided to group results according to the similarity of properties related to mineralization into environmental factors (18.6%), ecosystem/vegetation (14.52%), management (7.64%), soil physicochemical properties (34.65%), organic matter (16.05%), and microbiota (6.37%). The measurements of the response variables were 16.2% using N content in soil (as ammonium, nitrates, Organic N and Total N), and 83.88% represent N in the process of mineralization, including potentially mineralized N. As  $N_{min}$  is the dependent variable, the results included 109 independent variables, of which 47.7% presented seemingly inconsistent results, which means different effects in  $N_{min}$ . The difference in results was found to be related mostly to a difference in ecosystems or variable interactions. We conclude that acquiring a general prediction model for  $N_{min}$  or constructing a specific equation for local conditions poses a limitation to optimizing N management for crop production. A more useful strategy is to generate a prediction model for  $N_{min}$ , including significative soil and weather conditions, within a



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region and ecosystem; thus, the information can support soil and crop management decisions.

**Keywords:** Soil properties, N availability, predicting models, organic matter decomposition, ecosystems

## INTRODUCTION

Nitrogen (N) is an essential nutrient for plants and a limiting factor in primary production<sup>[1,2]</sup>. Plants obtain N from the soil in ionic forms, which are products of the decomposition of organic matter, a process driven mostly by soil microbes and is called mineralization<sup>[3]</sup>. Nitrogen mineralization ( $N_{min}$ ) and its availability in soil are influenced by several factors, such as soil properties and environmental variables, used in N predicting models<sup>[4,5]</sup>. Specifically,  $N_{min}$  is influenced by temperature<sup>[6,7]</sup>, mean annual precipitation<sup>[1]</sup>, clay content<sup>[6,8]</sup>, humidity<sup>[9]</sup>, organic matter<sup>[1]</sup>, pH<sup>[1,6]</sup>, microbial activity<sup>[10,11]</sup>, and microbial community composition<sup>[12]</sup>.

Various studies have been conducted on the association of these variables with  $N_{min}$ , yielding consistent results in some studies and inconsistent results in others. For example, a positive correlation has been shown consistently between microbial activity and  $N_{min}$  across different studies<sup>[1,6,10,11]</sup>. In contrast, the correlation between clay content and  $N_{min}$  was found to be largely inconsistent, either negative<sup>[13]</sup> or positive<sup>[14]</sup>, or there was no correlation between clay content and  $N_{min}$ <sup>[1]</sup>. In another example, Li *et al.* found that  $N_{min}$  was negatively correlated with pH<sup>[1]</sup>, while Liu *et al.* reported that  $N_{min}$  was generally suppressed by soil acidification<sup>[6]</sup>. Even within the same study, results did not always match. For example, it has been found that the mean annual precipitation (MAP) is related to  $N_{min}$ , but this relationship is not demonstrated in wetlands<sup>[1]</sup>.

The cause and frequency of these discrepancies are unclear. However, it has been inferred that the data from different ecosystems may contribute to these inconsistencies<sup>[1,6]</sup>. Other reasons for contrary results may be the differences among the methodological tools used in characterizing various variables and analyzing their relationships. An example is microbial activity measured as microbial biomass, basal respiration, enzymatic activity (hydrogenase, nitrogenase), phospholipid fatty acid concentration, microarrays, and sequencing<sup>[15]</sup>.

The inconsistencies are found when determining the influence of soil and environmental factors on soil  $N_{min}$  and availability. As a result, the type and strength of their influence make developing nutrient prediction techniques difficult, resulting in the progress of soil management strategies for maintaining crop production and reducing soil degradation inefficient or ineffective. The specific reasons for the discrepancies can vary depending on the factor. In this review, we hypothesize that inconsistencies can be found in several variables, like clay content, pH, and soil temperature, among others. Also, soil management and the type of ecosystem have no clear correlation with  $N_{min}$ . Therefore, we aim to perform a systematic review of the literature on  $N_{min}$  to ascertain the influence of soil properties and environmental variables on  $N_{min}$  and identify variables with inconsistent results. To accomplish this, we aimed (1) to build a database of soil properties and environmental variables that have examined  $N_{min}$ , detailing the analysis used; (2) to identify the variables that have shown different results in their relation to or influence over  $N_{min}$ ; and (3) to detect the possible source of discrepancies found in results of analysis relating different variables to  $N_{min}$ . This systematic review can guide research focused on predictive modeling of mineralized N or N availability in soils by assembling and synthesizing information about the factors driving or influencing mineralization and the outcome of the relationship analysis.

## MATERIALS AND METHODS

The initial scope of the chosen topic was performed, after which a work scheme was planned considering the recommendations to construct systematic reviews found in Cochrane<sup>[16]</sup> and the work on reviews done by Koutsos *et al.* and the Collaboration for Environmental Evidence<sup>[17,18]</sup>.

The article search was carried out in Spanish and English, independently by three researchers in the Jstor and ScienceDirect databases, followed by a grey literature search in Google Scholar. The search string strategy for databases using the Boolean operators was: (factor OR “soil properties”) and “soil nitrogen mineralization”; and in Spanish (factor OR “propiedades del suelo”) and “mineralización de nitrógeno”.

During the compilation of research articles, a database was filled independently by the searchers using ACCESS. The publishing information was obtained for each scientific article considered relevant to the review based on the title and abstract. The metadata of this database consisted of titles, authors, journals, and other publishing information, as well as abstracts. The three independent databases obtained were merged, and the duplicates were eliminated. The remaining articles were screened based on the eligibility criteria and the focus of this review by experts. Three consistency of inclusion checks were performed. The first check was from the independent databases of the searchers, using the titles of 10% of articles of each database to determine the inclusion of articles that focus on relating soil properties and environmental variables to N mineralization. The second check was conducted after the merge and duplicate elimination using the abstracts of 5% of the articles. The last check was performed after screening and critical appraisal by the experts by determining the percentage of articles that only one, only two, only three or the four evaluators consider relevant to be included in the review.

### Criteria for selecting studies

Determination of articles to be included in the study during expert appraisal was performed considering the following criteria.

#### *Inclusion criterion*

Articles aiming to determine, relate or predict  $N_{min}$  or availability in soils, using soil chemical, physical or biological properties, and environmental factors as the independent variables to relate to nitrogen.

#### *Exclusion criterion*

Articles without specifications of the methods used to determine the variables (specific variables and units) and their relationship (type of data analysis) are excluded. For instance, when a simple comparison of the variables is made without relating them. We decided to exclude publications before 1990 to limit the search and maintain consistency in the methodologies used to measure mainly soil N. Since the objective was to include relational or cause-effect analyses, the date cutoff also eliminated a lot of mainly descriptive or comparative studies more common before 1990.

### Data collection and analyses

The studies approved after the criteria filter were exhaustingly revised to extract the data necessary for the review, which were stored in a database designed in ACCESS for this review. The database included general information about each study (source, citation, and reference) and article registry from the first database. The information extracted from each article included sample size, ecosystem studied, conditions of the experiment (natural, field incubation, greenhouse, and laboratory), independent variable, dependent variable, statistical analysis to determine the significance of variable relationships, as well as *P*-value or significance determined.

We summarized the studies for each independent variable from the second database and determined the least studied variables. We also obtained the number of relationships analyzed in the included articles, the variables studied, and the proportion of studies where a significant relationship was found. As a result, the consistency in the results for the influence of each factor and the proportion for each different outcome was determined. A summary of the process to follow for the realization of the proposed systematic review is shown in Figure 1.

## RESULTS AND DISCUSSION

### Literature search on N mineralization

The literature search in Jstor and Science Direct resulted in 94 and 856 English publications, respectively, and no Spanish publications. An internet search in Google Scholar resulted in 8,500 English and 258 Spanish publications. After eliminating duplicates and combing through titles for relevance, we obtained abstracts of 749 studies, of which 129 were passed to the inclusion and exclusion criteria screening. A total of 90 studies were considered for this review, from which we extracted 788 relational results from various statistical analyses, including analysis of variance, linear and non-linear regression, correlation, multiple regression, principal component analysis (PCA), path analysis, and structural equation models. In all these, the objective was to test the influence of different factors on  $N_{min}$  or availability.

Nitrogen has been widely studied because of its importance as a limiting nutrient for plant growth, ecosystem services, and crop productivity. Therefore, there is a consistency in the measurements of this nutrient. These measurements are generally based on determining ammonium and nitrates by colorimetry and using the Kjeldahl method. Other methods, like the measurement of the  $^{15}N$  isotope, have also been used<sup>[19]</sup>. From these measurements, 16.12% of the analysis included here represents N as the content in soils (as Ammonium, Nitrates, Inorganic Nitrogen, Organic Nitrogen, and Total Nitrogen), and 83.88% represents N in the process of mineralization, including Potentially Mineralized Nitrogen ( $N_0$ )<sup>[8]</sup>, N ammonification ( $N_{amm}$  or  $R_{amm}$ ), nitrification ( $N_{nit}$  or  $R_{nit}$ )<sup>[20]</sup> of which the most represented (67.39%) is N mineralization ( $N_{min}$ ), which is sometimes measured as Net  $N_{min}$ <sup>[21]</sup>, or Gross  $N_{min}$ <sup>[19,22]</sup>, and in different rate units (e.g.,  $mgN\ m^{-2}d^{-1}$ ,  $mgN\ Kg^{-1}$ ,  $mgN\ m^{-2}d^{-1}$ ,  $mgN\ g^{-1}$ , %N mineralized, and  $\mu gN\ g^{-1}\ month^{-1}$ ).

The papers included in this review were from 28 countries spanning five continents [Table 1]. Besides, two of the papers were global<sup>[1,6]</sup>, including locations from all continents, and four papers did not specify the country the soil samples originated from since they worked under lab or greenhouse conditions. The continent best represented was Europe, with 20.5% of the countries included, followed by America, Asia, Oceania, and Africa (19.4, 15.2, 14.29, and 5.6%, respectively).

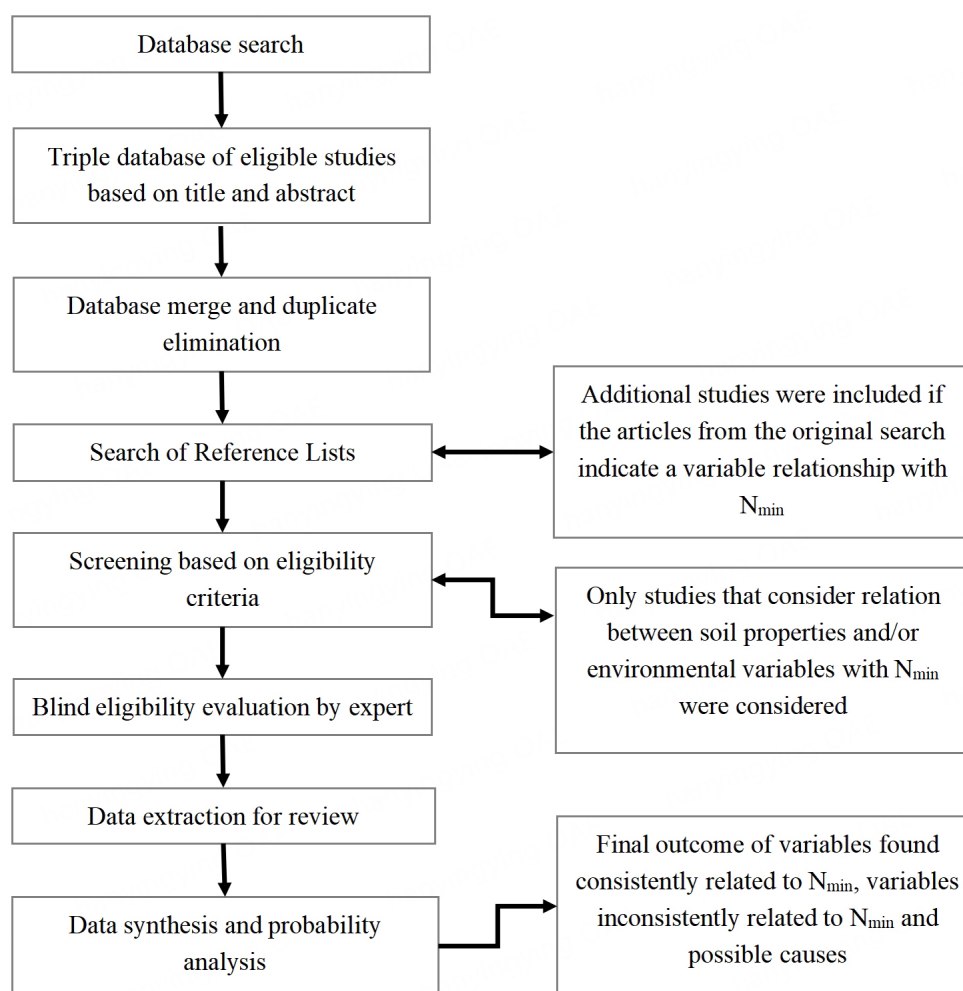
In America and Asia, the countries represented are distributed in temperate, subtropical, and tropical climate zones. On the other hand, Europe and Oceania only include temperate zones, and the three African countries are in the subtropical and equatorial zones.

### Factors relevant to N mineralization

Multiple factors have been studied to understand how they influence  $N_{min}$ . A total of 785 records were grouped into environmental factors (18.6%), ecosystem/vegetation (14.52%), management (7.64%), soil physical and chemical properties (34.65%), organic matter (16.05%), and soil microbiota (6.37%). In addition, there were two independent variables in 17 records, which were not considered in these groups unless they were in combination with another factor, in which case they were with that factors' group. These variables included laboratory incubation time and sites that represented random plots to have enough samples.

**Table 1. Countries where soil samples of studies originated. Number of papers from each country in parenthesis**

Continent	Countries/Regions
America	Canada (4), United States (17), Mexico (1), Costa Rica (4), Bolivia (1), Brazil (1), Argentina (2)
Europe	Austria (1), Belgium (1), Spain (3), Cyprus (1), Germany (1), Netherlands (6), Scotland (4), Switzerland (1), Turkey (2)
Africa	Tunisia (1), Kenya (1), Egypt (1)
Asia	China (24), Mongolia (4), Taiwan (1), Tibet (1), Japan (1), India (1), Iran (1)
Oceania	Australia (2), New Zealand (1)

**Figure 1.** Study design summary.

### *Environmental factors*

A total of 33 papers included environmental factors as explanatory variables to N availability or mineralization. Most of the environmental factors can be divided into topographic or climate variables. We found 36 records of topographic variables that include four instances in which topography was a factor with levels having different topographic characteristics<sup>[23,24]</sup> or several topographic variables meshed into one<sup>[25]</sup>. There was a significant effect of topography on  $N_{min}$ , Total N (TN), and Available N (AN). Altitude has a significant effect on  $N_{min}$ <sup>[6,26]</sup>. However, the elevation was reported as not significant to TN<sup>[25,27]</sup> and AN<sup>[25]</sup>, indicating an influence on the process of mineralization but not on the N pool. Slope position was found

significant to TN<sup>[28]</sup> and N<sub>min</sub>, even interacting with texture<sup>[29]</sup>. Aspect and the Topographic Wetness Index significantly affected both TN and AN<sup>[25,27]</sup>. Slope length and horizontal curvature showed no influence on N<sup>[25,27]</sup>. The slope, stream power index, and Vertical curvature were inversely proportional ( $P < 0.05$ ) to AN but not significant to TN<sup>[25,27]</sup>, showing an influence on mineralized N but not on N contained in organic matter. The topographic variables are important to N because they measure the shape of the terrain, which influences the type of vegetation found, indicate whether the soil can accumulate or remain in place for enough time to impact nutrient accumulation, and even if texture (also impacted by topography) has the qualities to maintain the microbiome and nutrients. Annual Potential Evapotranspiration was the only climatic independent variable not found relevant to N<sub>o</sub> or N<sub>min</sub><sup>[30]</sup>. We only considered one study each for tides<sup>[31]</sup>, snow density<sup>[32]</sup>, environmental CO<sub>2</sub><sup>[33]</sup>, disturbance as burning and cutting<sup>[33]</sup>, and disturbance simulation as sieving<sup>[14]</sup>; for all, there was a significant influence on N<sub>min</sub> (CO<sub>2</sub> on N<sub>o</sub>), while drying the soil had no significant effect on N<sub>min</sub><sup>[14]</sup>. Erosion was studied by Wang *et al.* by comparing erosional to depositional soil, but they found that it only affected N<sub>min</sub> and N<sub>nit</sub>, but not N<sub>amm</sub><sup>[34]</sup>. Ma *et al.* found that wind disturbance significantly diminished N<sub>min</sub> and had an interactive effect with vegetation, indicating that the vegetation can change how the wind damages the soil processes<sup>[35]</sup>.

The most common environmental variable is temperature. This environmental variable has been considered as the Mean Annual Temperature (MAT)<sup>[6]</sup> and soil temperature<sup>[36]</sup>, or it has been manipulated in controlled environments to determine the effects of freezing<sup>[37]</sup> or warming<sup>[20]</sup> to study changes caused by extreme weather conditions and climate change. We considered 35 records with temperature as the independent variable, and only 37.14% were found significant. Dessureault-Rompré *et al.* found that MAT is inversely proportional to N<sub>min</sub> and N<sub>o</sub>, which coincides with the results reported by Urakawa *et al.* when MAT was related to Net N<sub>min</sub><sup>[30,19]</sup>. On the other hand, MAT has shown no significance to Gross N<sub>min</sub><sup>[19]</sup>, the same as the results reported by Liu *et al.* and Li *et al.*<sup>[6,1]</sup>. For all cases that considered a wide arrange of climates in their study<sup>[1,6]</sup>, if not latitudes in all cases (in Canada<sup>[30]</sup> and in Japan<sup>[19]</sup>), the location cannot be the source of the inconsistency. When the temperature was considered a freeze-thaw cycle<sup>[37]</sup>, it was found significant, elevating N<sub>min</sub> in the first cycle but diminishing it after the third. The influence was found to be inconsistent at different depths. When the climatic temperature was included in the experiment, it was shown to be insignificant<sup>[38]</sup>. On the contrary, Owen *et al.* found it to have a positive correlation with Net N<sub>min</sub> in the *Tsuga-Yushania* forest but not in the *Miscanthus-Yushania* grassland (and opposite results for Net N<sub>nit</sub>), indicating that the microclimate created by the vegetation can change the relevance of the climatic variables to N<sub>min</sub><sup>[39]</sup>. When the temperature was measured in the soil, Wang *et al.* did not find it significant in natural or plantation forests<sup>[36]</sup>. However, Hou *et al.* found it to be significant when measured both during the thawing and freezing periods. They reported a quadratic relation during the freezing period and an exponential relation during the thawing period<sup>[40]</sup>. When the temperature was considered as treatment in laboratory incubations, Song *et al.* reported that the higher the temperature, the higher would be the N<sub>min</sub>, N<sub>nit</sub> and N<sub>amm</sub> ( $P < 0.001$ )<sup>[20]</sup>, which coincided with the results found when tested at higher temperatures (20 °C and 25 °C) for N<sub>min</sub><sup>[41]</sup>. While the temperature was found to be significant to Inorganic N in soil, it was not the case for Organic N and N losses<sup>[42]</sup> when comparing 15 °C and 30 °C, indicating an influence of temperature on the mineralization of N, but not the organic matter or the loss of N by other processes.

The temperature was also considered a climatic index as growing degree days (GDD). The index of crop growth is defined as the number of degrees Celsius that the mean temperature is above five by the Environment Canada website. GDD was found to be negatively correlated with both N<sub>min</sub> and N<sub>o</sub><sup>[30]</sup>. Precipitation was considered in four papers with 13 recorded analyses. MAP was found to be positively correlated with N<sub>min</sub><sup>[36]</sup>. Li *et al.* found the same in analyses of global data and data from forests, grasslands, and croplands, but not in wetlands where water is already abundant, and input from rain is not reflected on



$N_{min}$ <sup>[1]</sup>. Contrary to this, Liu *et al.* did not find a correlation between  $N_{min}$  and MAP<sup>[6]</sup>. Although both papers were done by collecting peer-reviewed articles with sampling points from all around the world, the distinction can be because, in the work of Liu *et al.*,  $N_{min}$  was determined after laboratory incubation experiments, assuming that water availability was controlled<sup>[6]</sup>. Urakawa *et al.* also measured Gross and Net  $N_{min}$  after laboratory incubations and found no correlation to MAP<sup>[19]</sup>. Also related to water availability, a study on flooding comparing wetland types found differences in inorganic N, nitrates,  $N_{min}$  and  $N_{nit}$ , but no differences in Ammonium or  $N_{amm}$ <sup>[43]</sup>. In addition, it was found that while the aridity index was positively correlated with  $N_o$ , it did not correlate with  $N_{min}$ <sup>[30]</sup>. Latitude and seasons were also considered environmental factors, and while latitude was found to be negatively correlated with  $N_{min}$  in one study<sup>[6]</sup>, another work found it positively correlated only as Net  $N_{min}$  but not correlated as Gross  $N_{min}$ <sup>[19]</sup>. The first study<sup>[6]</sup> considered sampling points worldwide, but the latter only concerned positive latitudes (Japan). Of the 29 records with seasons or months of the year as explicative variables, 27 were found significant. The only insignificant results were from the interaction of season and flooding<sup>[43]</sup>, where the season on its own was significant but not interacting with flooding. In a study with five monthly measurements from the end of April to October, where a five-factor repeated measures ANOVA, Yao *et al.* found differences between the months in nitrates, ammonium and mineral N, but not in Net  $N_{nit}$ , Net  $N_{amm}$ , and Net  $N_{min}$ , probably because of samples in different vegetation types, soil texture, slope positions and depth in the soil<sup>[29]</sup>.

#### *Ecosystem/vegetation*

Factors related to vegetation or ecosystem were found in 40 papers. A total of 114 records were found for relational analysis with N dynamics or availability as the response variable and 11 independent variables, of which seven had inconsistent results. These variables can be divided into descriptive variables (chemical composition) and the presence or variability of plants (including a community or ecosystem). Biomass of vegetation was not found to be correlated with  $N_{min}$ <sup>[36]</sup>, TN, or inorganic N<sup>[44]</sup>, and neither was N fixation<sup>[44]</sup>. However, the toughness of the vegetation was found to be negatively correlated ( $P < 0.05$ ) to  $N_{min}$ <sup>[45]</sup>. The saturated water absorption ratio of the moss biocrust on the soil was found to be positively correlated with inorganic N ( $r = 0.659$ ) but not with TN<sup>[44]</sup>. The C content of the moss biocrust was found to be positively correlated with inorganic N ( $r = 0.612$ ) but not with TN<sup>[44]</sup>. The same results were observed for the N content ( $r = 0.584$  for inorganic N and insignificant for TN), indicating that the composition of the biocrust will affect N readily available in the soil but not the N in organic matter. Orwin *et al.* found that the N content of grass leaves was positively correlated with  $N_{min}$  ( $P < 0.05$ )<sup>[45]</sup>. On the other hand, Kooijman *et al.* found that the correlation depends on the grass species, where they reported a positive correlation of  $N_{min}$  with N content of shoots of *Ammophila arenaria* ( $r = 0.91$ ) and *Calamagrostis epigeos* ( $r = 0.59$ ), but not in case of *Elytrigia atherica* ( $r = 0.45$ )<sup>[46]</sup>.

Several works have studied differences in mineralized N for the presence and absence of plants. The absence of plants can occur naturally through constant removal by animals<sup>[31]</sup> or anthropogenically when canopy forest gaps are created in vegetation years before<sup>[47]</sup> or when existing vegetation is purposefully removed for study purposes<sup>[10]</sup>. Studies found a higher  $N_{min}$  in the presence of plants. However, when considering a vegetation gap gradient, the results showed less mineralization in the transition zones than below the canopy and at the center of the gap<sup>[47]</sup>. When considering roots, Norton *et al.* found higher mineralization levels near the roots than in cases where there were no roots ( $P < 0.05$ )<sup>[48]</sup>. Conversely, Song *et al.* found that root additions did not affect the soil  $N_{min}$  and  $N_{amm}$  rates. However, Song *et al.* experiment was performed under different temperatures and depths of soils in a laboratory incubation experiment, and the results were inconsistent under different treatments<sup>[20]</sup>. These results show an interaction of climate and vegetation as explanatory variables to mineralization.

When considering vegetation cover, Knops *et al.* found that the cover of C3 grass, C4 grass, and forbs demonstrate a positive correlation with TN<sup>[49]</sup>. On the hand, the cover of Cryptograms negatively correlated with TN. Li *et al.* used a cover vegetation index from satellite images and found that vegetation coverage positively correlated with TN and available N<sup>[25]</sup>. However, the study found no significant relationship when using a randomized block analysis with two years as the blocks and four levels of canopy clearcutting as the treatments. The study found high  $N_{min}$  in the cleared areas during the first year after cutting due to the initial abundance of organic matter. However, in the following year, the  $N_{min}$  was much lower in the areas with little or no canopy compared to the cut areas, likely due to the absence of a source of organic matter<sup>[50]</sup>. Several studies have measured  $N_{min}$  levels in specific plant species from forests<sup>[51,52]</sup> and a semiarid woodland<sup>[53]</sup>. The studies revealed that the  $N_{min}$  levels vary between different plant species. Ewel also found differences in  $N_{min}$  under different trees in the plantation ( $P = 0.025$ ) in the absence of an interactive effect of the species and their rotation ( $P = 0.196$ ), indicating that the species is the determining factor<sup>[54]</sup>.

De Boer and Kester found no differences between species in a forest when comparing the underground species<sup>[55]</sup>. Similar to the results of Van Der Krift and Berendse, who studied  $N_{min}$  levels across 14 monocultures of species of grasses and dicots, De Boer and Kester observed that grouping these species based on fertility<sup>[56]</sup> revealed significant differences ( $P < 0.001$ ). This observation suggests that the traits of different species can be a determining factor for  $N_{min}$ . Yao *et al.*, in their study of  $N_{min}$  levels among species of shrubs in an arenosol soil, found that at a soil depth of 0-10 cm, there were significant differences in  $N_{min}$  among species ( $P = 0.012$ ), but those differences were not maintained at a depth of 10-20 cm. Their study determined that some species of shrub (*Salix psammophila* C.) did not contribute to  $N_{min}$  as there were no differences to bare soil<sup>[57]</sup>. Barrios *et al.* compared  $N_{min}$  in different crops under aerobic and anaerobic conditions and found significant differences between the crops in both aerobic ( $P = 0.033$ ) and anaerobic ( $P = 0.013$ ) conditions<sup>[58]</sup>. Most studies on vegetation communities or ecosystems found significant differences (67.86%) between ecosystems<sup>[59,60]</sup>, plant communities<sup>[61,62,63,64]</sup> or land use<sup>[27,61,65]</sup>. Johnson and Wedin observed differences ( $P < 0.001$ ) when comparing a grassland and a forest. In addition, they observed a transition in  $N_{min}$  levels between a grassland and a forest, indicating an increased  $N_{min}$  level towards the forest<sup>[66]</sup>. Significant differences in  $N_{min}$  levels between communities were not observed only in one study when comparing abandoned agricultural soil, pastures, and woodlots that had not been used for 90 to 120 years<sup>[52]</sup>. However, even in this case, the  $N_{min}$  level was always different except for one month of the year (August of the year before), while significant differences were observed in the rest of the samplings ( $P = 0.017$ ). Fisk *et al.* didn't find a difference between an old and a secondary forest on Net  $N_{min}$  or Gross  $N_{min}$ <sup>[67]</sup>. A study on bamboo invasion in an evergreen broadleaf forest found that the invasion reduced  $N_{nit}$  and  $N_{min}$  significantly ( $P < 0.05$ ), while  $N_{amm}$  remained intact<sup>[68]</sup>. In a comparative study of a pine forest, a spruce-fir forest, and an Erman's birch forest<sup>[35]</sup>, no significant differences ( $P = 0.053$ ) were found. However, an interactive effect with soil depth ( $P = 0.01$ ) was observed. The noted study was focused on wind disturbance, and the soil depth interaction can explain the lack of difference between forests instead of the different communities. These results are similar to a study comparing savanna woodland, pasture, and a *Eucalyptus* plantation<sup>[69]</sup>, where no significant difference was observed between ecosystems ( $P = 0.160$ ). However, an interaction with soil depth ( $P < 0.001$ ) was found when the response variable was  $N_o$ . Another study comparing a tropical semideciduous forest, a secondary forest, a coastal dune crest, and coastal dune slack<sup>[70]</sup> found significant differences only in Net  $N_{amm}$  ( $P = 0.007$ ). In contrast, Net  $N_{nit}$  ( $P = 0.079$ ) or Net  $N_{min}$  ( $P = 0.069$ ) demonstrated no difference. When analyzing the interaction with the months tested, they found no ecosystem and time interaction for  $N_{amm}$  ( $P = 0.292$ ). However, they observed the interaction for  $N_{nit}$  ( $P = 0.001$ ), indicating that the seasons can affect each ecosystem differently. This observation suggests the need to consider the diversity of vegetation in each ecosystem and their properties in demonstrating significant differences. Zhao and Li found significant differences in Net  $N_{min}$  for 2012 and 2013, as well as in gross  $N_{min}$  ( $P < 0.05$ ) when comparing a meadow and a shrub. They also found a significant interaction of



the aspect vegetation with the months collected ( $P < 0.01$ ) in 2013, while an interaction was not found in 2012. This observation suggests that seasonal changes and other specific climatic changes can affect the mineralization of  $N_{min}$ <sup>[71]</sup>. Wang *et al.* found differences between ecosystems when comparing grasslands to the forest and natural forests with plantation forests<sup>[36]</sup>. They also found significant positive correlations between  $N_{min}$  and the Shannon-Wiener diversity index for trees ( $r = 0.71$ ), herbs ( $r = 0.52$ ), and Margalef's tree diversity index ( $r = 0.72$ ), indicating that a place with a greater diversity of plants will have a higher  $N_{min}$ .

### Management

Soil management modifies several soil properties that influence the process of mineralization. The eight management variables found in our results come from 27 papers with 60 records, of which three were found with inconsistent results. The management factors could be divided into two categories: management regarding the vegetation on the soil (e.g., afforestation, clearfelling), and management regarding the soil (e.g., tillage, amendments). The most studied management variable (60% of the records) in this paper is amendments since nutrient availability is the first limiting factor to crop productivity, followed by water availability. The amendments found in this recompilation were urea<sup>[33]</sup>, chemical fertilizers for nitrogen<sup>[10,48,72,73]</sup>, chemical fertilizers for phosphorous and potassium<sup>[28,72,74]</sup>, biochar<sup>[37]</sup> alone or with straw<sup>[40]</sup>, broiler litter<sup>[75]</sup>, liming<sup>[76]</sup>, green manure<sup>[77]</sup>, kelp<sup>[78]</sup>, bioinput<sup>[79]</sup>, manure<sup>[73,79]</sup>, and digestates<sup>[80]</sup>. Results show a significant change due to the use of amendments in 80.5% of cases. Fu *et al.* tested biochar in a laboratory experiment and did not find a significant effect<sup>[37]</sup>. They evaluated biochar under different moisture levels and at different soil layers and found no interactive effect of the factors. On the contrary, Hou *et al.* found that biochar demonstrates a higher level of mineralization compared to the control group, but lower than the use of a straw<sup>[40]</sup>. Both studies used the straw to produce the biochar at temperatures over 500 °C. The first study used biochar with a pH of 8.5 with 1.28% ( $\pm 0.13$ ) N, while the second study used biochar with a higher pH (9.68) with N content (1.57%) as the main differences between the biochar samples used. Chen *et al.* found that N enrichment increases  $N_{min}$  ( $P < 0.05$ ), and the effect was maintained regardless of the plant presence (no interactive effect with the presence/absence of plants)<sup>[10]</sup>. Norton and Firestone found no significant effect on the ammonification rate when using an ammonium N addition<sup>[48]</sup>. Hassink also found no effect on  $N_{min}$  when measuring the percent N mineralized per day<sup>[13]</sup>. Miranda *et al.* found that using the commercial fertilizer had no effect on ammonium in soil when comparing a commercial organic fertilizer and manure<sup>[79]</sup>. However, the commercial fertilizer increased nitrates (and inorganic N as a consequence). They found that manure increased nitrates and ammonium, while the use of commercial fertilizer and manure demonstrated an interactive effect on nitrates and ammonium. However, such an interaction was not observed on inorganic N<sup>[79]</sup>.

Only one study considered crop rotation<sup>[54]</sup> and found it to impact  $N_{min}$  significantly. When comparing cultivated versus uncultivated soils, the former had a higher  $N_{min}$  ( $P < 0.001$ ). In addition, there was an interaction with the usage of different plant residues ( $P < 0.01$ ) in the soil as a source of organic matter<sup>[81]</sup>. Afforestation of shrubs was implemented to curb desertification, which was found to raise  $N_{min}$  and  $N_{nit}$ <sup>[82]</sup> throughout the afforestation. A study on clearfelling shows that burning and cutting down a forest increases  $N_{min}$  initially due to the organic matter input into the soil, especially in burnt forests. However, the increase in  $N_{min}$  level decreases below those in the undisturbed forest within two years<sup>[83]</sup>, probably due to the absence of a yearly newfound organic matter source. Another form of vegetation clearing is grazing, which has been studied with different animals. The intensity of grazing by livestock was compared using various treatments, including no grazing, moderate grazing, and heavy grazing. Shariff *et al.* found that there was no difference between no grazing and heavy grazing, but moderate grazing considerably increased the  $N_{min}$  level ( $P < 0.05$ )<sup>[84]</sup>. On the contrary, Biondini *et al.* found differences only in July, and the not grazed treatment presented significantly higher Net  $N_{min}$  than moderate and heavy grazing ( $P < 0.05$ )<sup>[85]</sup>. The ungrazed and

moderately grazed treatments demonstrated higher  $N_{min}$  levels than the heavily grazing treatment when the entire growing season is considered<sup>[85]</sup>. Hassink compared grazing by cows versus a mowing treatment on a specific sandy soil ( $P < 0.05$ ) and concluded that the former resulted in higher  $N_{min}$ . However, the results were not repeatable on the other sandy or loamy soils measured ( $P > 0.05$ )<sup>[13]</sup>. Frank and Groffman found that grazing by wild ungulates increased  $N_{min}$  levels in Yellowstone Park ( $P < 0.05$ )<sup>[64]</sup>. A study concerning vole presence indicated that grazing affected  $N_{min}$  levels only in one of the sites studied<sup>[86]</sup>. This site had different dominant forbs and graminoids than the others and demonstrated a higher mineralized N level when exposed to vole presence ( $P = 0.045$ ). Grazing by geese in a salt marshland diminished ( $P < 0.01$ ) the Net  $N_{min}$ <sup>[31]</sup>. A soil management practice studied is tillage. It was found that tillage increases  $N_{min}$ <sup>[76]</sup>. The strip-tillage promoted a more readily mineralizable pool of N<sup>[75]</sup> when comparing conventional and strip tillage. The more evident effects observed were the interaction with amendments. The  $N_{min}$  level was significantly higher with strip-tillage when combined with broiler amendments than when no amendments were used<sup>[75]</sup>. Interactive effects were also observed when combining tilling and liming amendment applications<sup>[76]</sup>. A management variable considered was the age of an established vegetation community. Three studies found that the older the community, the higher the nitrogen pool (NT) in abandoned cropland<sup>[49]</sup> and a tea plantation<sup>[87]</sup>. Moreover, higher  $N_{min}$ <sup>[13]</sup> levels in a grassland indicate that any changes in soil use will negatively affect  $N_{min}$  or availability.

#### *Soil physical and chemical properties*

A total of 27 physicochemical properties related to N mineralization or availability were found in 272 analyses recorded across 50 papers. Twelve of these independent variables had inconsistent results. Soil types and parent materials were considered in this category because they represent differences in the combination of physicochemical properties. All studies that compared soil types found differences in TN and AN<sup>[25,27,28]</sup>. Several studies found that parent material can affect N availability or mineralization, but not all studies demonstrated this effect. AN was found to be affected by parent material<sup>[25]</sup>. However, when TN was used as the dependent variable, Zhang *et al.* found differences when comparing alluvial, thick and thin shale, and sandstone<sup>[28]</sup>. On the other hand, in studies that included alluvial deposits and different types of purple shale, there were no significant differences in TN between the different parent materials<sup>[25,27]</sup>. Nevertheless, TN includes N contained in organic matter and finding differences can depend on the capacity of the soil to retain organic matter. Hence, when the parent material does not represent significant differences in texture or porosity, it is possible to misinterpret the differences between the materials. For example, a study comparing the  $N_{min}$  levels of Gypsum, Marl, and Serpentine found that the latter had higher  $N_{min}$  than the other two soil types, but only after 42 days of incubation<sup>[88]</sup>. On the contrary, a study on the soil derived from Serpentine (the one with the highest sand content) comparing silicate and limestone parent materials indicated no differences in gross  $N_{min}$ <sup>[59]</sup>. Moreover, soils that were tested for cambisol and luvisol were characterized as having a finer texture, which the same study found to be correlated with  $N_{min}$ .

We found seven soil physical properties that have been studied concerning N availability and mineralization. The only ones without inconsistent results were included in only one research paper, including drainage<sup>[74]</sup>, aggregate size<sup>[87]</sup>, and field capacity<sup>[44]</sup> and were found to be positively related to  $N_{min}$ , TN, and inorganic N, respectively.

The other variables studied were bulk density, depth, porosity, and texture (as one or all the particle sizes). There were some inconsistencies in the results of each property. Bulk density was used as an explanatory variable for N availability and mineralization in nine papers and was found to be negatively related to the dependent variable in 52% of the 25 analyses. For soils originating from natural environments, plantations, crops, restoration areas and using amendments, the bulk density was found to be negatively correlated with

$N_{\min}$ <sup>[63]</sup>,  $N_o$ <sup>[8,70]</sup>, inorganic N<sup>[44,89]</sup>, and Total N<sup>[44]</sup>. However, two studies found no significant correlation between the variables<sup>[62,71]</sup>, one carried out on forests and plantations and the other on grassland, shrubbery, and plantation soils. Breland and Hansen compared the impact of two levels of manure and green manure compaction on the control of growing grass. They found a significant difference only when using green manure, indicating that the density of the soil influences mineralization only under certain circumstances related to organic matter<sup>[90]</sup>. Yang *et al.* correlated  $N_{\min}$  with bulk density monthly from May to September on 10 cm of topsoil<sup>[21]</sup>. They found a significant correlation only from July to September, indicating an influence of temporal factors<sup>[21]</sup>. The study was performed *in situ*. Since  $N_{\min}$  has similar patterns to precipitation, it is possible that in May and June, there was not enough variation in  $N_{\min}$ , or it was too low to detect a correlation with bulk density. N has been compared at various depths of the soil, and it was found to be highest in topsoil than in layers underneath.

Soil texture was studied as percentages of clay, silt, and sand to relate them to N, and the results were contradictory.  $N_{\min}$  was found to be different when two types of soil with different textures were compared<sup>[29]</sup>. The sand percentage had a negative correlation with  $N_{\min}$  and  $N_o$ <sup>[30]</sup>, and the clay percentage demonstrated a positive correlation with  $N_{\min}$ <sup>[30]</sup> and  $N_o$ <sup>[30,91]</sup>. Silt + Clay percentage was not found to be correlated with  $N_{\min}$ <sup>[13]</sup>. Three studies used each particle size as an independent variable in the correlations. Martínez *et al.* found them all significantly correlated with  $N_o$ <sup>[8]</sup>. However, only two studies found the clay to be correlated with  $N_o$ <sup>[92]</sup> and  $N_{\min}$ <sup>[59]</sup>. Clay was correlated with Organic Nitrogen, inorganic N, and N losses but was only significantly related to Organic N<sup>[42]</sup>. Porosity was correlated with Inorganic N<sup>[89]</sup> and was found to be positively correlated in both amended and unamended soils with high *r* values (0.99 and 0.98, respectively). When correlated with the porosity of different size pores (macropores, coarse mesopores, fine mesopores and micropores), no correlation was found between inorganic N and porosity in amended and unamended soils. The correlation was found only to macropores and micropores (*r* = 0.95 and *r* = 0.99, respectively). These results indicate that density matters to mineralization more in relation to the effective porosity of the soil, given by the distribution of particle sizes and compaction.

Moisture is considered in the physicochemical attributes of soil in this review. The results show a variety of techniques in which soil moisture has been studied concerning N mineralization and availability. Moisture as water content and water holding capacity was found to be positively correlated with  $N_o$  in a laboratory incubation experiment of agricultural and grassland soils<sup>[91]</sup>. Water content was also found to be positively correlated with  $N_o$  by Campos *et al.*<sup>[70]</sup>. When studied in the context of TN and inorganic N, a positive correlation to moisture was found<sup>[44]</sup>. Franzluebbers *et al.* conducted a non-linear regression of  $N_{\min}$  (as a percentage of mineralized N) as a function of moisture for soils under constant moisture and dry-wet cycle management<sup>[93]</sup>. They found higher  $N_{\min}$  levels under constant moisture<sup>[93]</sup>. A study found a significant logarithmic correlation of  $N_{\min}$  with moisture during the freezing period of the soil and a significant quadratic correlation during the thawing period<sup>[40]</sup>. Fu *et al.* included moisture content (%) as a factor in a multi-way ANOVA and found significant differences between the moisture treatments (15%, 20%, and 25%)<sup>[37]</sup>. Contrary to these studies, others found no correlation between moisture and  $N_{\min}$ <sup>[39,55,62]</sup>. Considering the variety of relations found in the previously mentioned studies, the lack of a correlation can be due to the lack of variability in the moisture content that prevents establishing a trend or the specific type of relation. Breland and Hansen compared two levels of water content and found no significant differences in  $N_{\min}$  between them<sup>[90]</sup>. In a multifactor ANOVA comparing two levels of water content (12% and 18%), inorganic N was found to be significantly different, while organic N and N losses demonstrated no significant difference<sup>[42]</sup>. Inorganic N is closely related to microbial activity, which requires the presence of water. When comparing 60% and 100% moisture intensity in a three-way ANOVA, there were no significant differences in  $N_{\min}$ . However, when comparing the number of dry-wet cycles in the same study,

there were differences among treatments<sup>[94]</sup>, indicating the higher importance of the drying cycle than the quantity of water. A multiple linear regression study was conducted to correlate water content and  $N_{min}$  in different months of the year (May to September) and at two soil depths (0-10 cm and 10-20 cm). The moisture was found to be significant only in September at a 10-20 cm depth<sup>[21]</sup>. When the correlation was done on three different dates at alpine grasslands of two different mounts, a negative correlation was found significant in the September-October period but only in one of the mounts<sup>[26]</sup>. The same study found a significant negative correlation when the soils were incubated *in situ*. These results indicate temporality significance in the importance of water to  $N_{min}$ .

One of the most studied attributes of soils with  $N_{min}$  is pH. Several studies found no correlation between pH to  $N_{min}$ <sup>[19,30,55,62]</sup> or  $N_o$ <sup>[30,92]</sup>. When there was a significant correlation, the results varied. The negative correlations of pH with  $N_{min}$ <sup>[6,36,63]</sup> and  $N_o$ <sup>[8,70,91]</sup> were the most common. Yang *et al.* correlated  $N_{min}$  with pH in ten analyses performed under different months and soil depths<sup>[21]</sup>. They found a significant positive correlation only in July at a 10-20 cm depth, and the rest were insignificant<sup>[21]</sup>. Finding a significant correlation between pH and  $N_{min}$  may depend on the variability of the data and the range of pH values. Soils that are too acidic or too alkaline can diminish microbial activity. The optimum soil pH can be in the middle range, resulting in a non-linear relationship. This premise has been confirmed in one study that revealed a significant quadratic correlation<sup>[46]</sup>.

Electric conductivity, as a measure of soluble salts in soils, was found to be positively correlated with  $N_o$  in a lab incubation study<sup>[70]</sup>. However, no correlation was found in a field study<sup>[92]</sup>. Cation exchange capacity was found to be correlated with  $N_o$ <sup>[70]</sup> but not with gross  $N_{min}$ <sup>[59]</sup>. Phosphorus addition was not found significant to  $N_{min}$ <sup>[22]</sup>. When phosphorus was correlated with  $N_o$ , one study found the correlation significant and negative<sup>[8]</sup>, while another found no significance<sup>[91]</sup>. To find correlations, the attributes need enough variability to allow one variable to change depending on the variation of another variable, which is not always the case. We found chemical attributes that were studied in relation to  $N_{min}$  only in one of the publications included in this study. Oxygen in the environment was used in three-level treatments, and ANOVA analyses show that there were greater  $N_{min}$  and  $N_{nit}$  when there was more oxygen in the environment. However, there were no significant differences in treatments for  $N_{amm}$ <sup>[87]</sup>, showing that nitrates have a more significant influence than ammonium in establishing the pattern that  $N_{min}$  follows. Base saturation<sup>[59]</sup> and calcium<sup>[19]</sup> were found to be positively correlated with  $N_{min}$ . The N:P ratio was found to be positively correlated with  $N_o$ <sup>[91]</sup>. On the other hand, the C:P ratio was found to be negatively correlated with  $N_o$ <sup>[91]</sup>, as was the carbonate content<sup>[92]</sup>. In addition, hydraulic conductivity<sup>[70]</sup> was negatively correlated with  $N_o$ . Different dilutions of soil extracts that contained allelopathic compounds from previous plantations in the soil have been tested<sup>[95]</sup>. It was found that  $N_{min}$  and  $N_{nit}$  were lower at higher allelopathic compound content. Salinity has been tested separately as Chlorine ( $Cl^-$ ) and Sodium ( $Na^+$ ) content and related to Net and Gross  $N_{min}$ , but no significant correlation was found.

### Organic matter

A total of 126 analyses related to soil organic matter variables were divided into 21 distinct variables from 18 papers. These variables were measured as organic matter content in the soil and different characteristics from the organic matter fraction of the soil or the litter. The organic matter has been measured as the litter on the soil, fractions of the organic matter, and chemical properties of the organic matter. In the measurements of litter, carbon content<sup>[44,68]</sup> and biomass<sup>[36,44,68]</sup> have not been found significant to N availability or mineralization, while litter decomposition ( $r = -0.85$ )<sup>[46]</sup>, litter lignin content in soil ( $r = -0.833$ ) and in crop ( $r = -0.861$ )<sup>[96]</sup>, and litter C:N ( $r = -0.58$ )<sup>[68]</sup> ratio have been found negatively correlated with  $N_{min}$ . The C:N content was also negatively correlated with  $N_{nit}$  ( $r = -0.66$ )<sup>[68]</sup>. The N content

in the litter was only found to be significantly correlated with  $N_{amm}$  ( $r = 0.60$ ) but not to  $N_{nit}$ ,  $N_{min}^{[68]}$ , TN or inorganic  $N^{[44]}$  when using Pearson's correlation, while in a PCA was found significant to  $N_{min}^{[48]}$ . Raiesi found differences in the  $N_{min}$  when comparing plant residues as the litter source ( $P < 0.001$ )<sup>[81]</sup> and when separating the parts of the plant used as litter. Only the foliage litter was found to be significantly correlated with  $N_{min}$  ( $r = 0.55$ ), but not the plants' branches, stems, or roots<sup>[36]</sup>. The litter turnover rate was found to correlate with  $N_{amm}$  ( $r = 0.65$ ,  $P < 0.05$ ) and  $N_{min}$  ( $r = 0.59$ ,  $P < 0.05$ ) but not with  $N_{nit}$  ( $r = 0.49$ )<sup>[68]</sup>. The annual litter production was found to be positively correlated with  $N_{min}^{[36,68]}$  but not significant to  $N_{amm}$  and  $N_{nit}^{[68]}$ .

De Neve and Hofman found that the water-soluble fraction in soil and crops is positively correlated ( $r = 0.746$  and  $r = 0.861$ , respectively) with  $N_{min}^{[96]}$  based on measurements made only on the organic matter of the soil. The dry weight of the soil organic matter (SOM) fraction was found to correlate with aerobic  $N_{min}$  only in the separated density  $< 1.13 \text{ g/cm}^3$  of the SOM<sup>[58]</sup> but not to higher density SOM or under anaerobic conditions. The C:N ratio in lignin of SOM was found to be negatively correlated with  $N_{min}$  in soil ( $r = -0.833$ ) and crop ( $r = -0.882$ )<sup>[96]</sup>, and in the SOM fraction, C:N was significant to  $N_{min}$  only under aerobic conditions with SOM densities under  $1.7 \text{ g/cm}^3$ <sup>[58]</sup>. Nitrogen in SOM has been measured in several studies. The moist extractable organic N was found to be positively correlated with  $N_0$  ( $r = 0.81$ )<sup>[91]</sup> in corn and grasslands, and N from the heavy fraction of organic matter was positively correlated with  $N_{min}$  ( $r = 0.854$ ) in paddy soils<sup>[97]</sup>. Zhang *et al.* found no significant correlation between Gross  $N_{min}$  and dissolved organic N ( $r = 0.372$ )<sup>[59]</sup>. Martínez *et al.* found a significant correlation of  $N_0$  with Nitrogen in fine organic matter particles ( $r = 0.83$ )<sup>[8]</sup> but not with Nitrogen in coarse organic matter particles ( $r = 0.17$ ), indicating that the size, which is related to ease of degradation, is important to N availability. Another study found  $N_0$  to be positively correlated ( $r^2 = 0.011$ ,  $P < 0.05$ ) with N in organic matter particles but not  $N_{min}$  ( $r^2 = 0.05$ )<sup>[30]</sup>. Barrios *et al.* found that  $N_{min}$  is correlated with N concentration in SOM but only under aerobic conditions<sup>[58]</sup>, which can happen under suboxic conditions since the mineral N liberated can be reused by the microbiota to maintain their metabolism in anaerobic conditions<sup>[59]</sup>. Measurements of C within organic matter had contradictory results.  $N_{min}$  was found to be positively correlated with heavy fraction C<sup>[1]</sup> and particulate organic matter C<sup>[30]</sup>.  $N_0$  demonstrated a positive correlation to moist extractable organic C<sup>[91]</sup> and particulate organic matter C<sup>[30]</sup>, while Zhang *et al.* found no correlation of gross  $N_{min}$  to dissolved organic C<sup>[59]</sup>. Moreover, Barrios *et al.* found no significance in the relation of  $N_{min}$  to C concentration in SOM unless it was with SOM densities less than  $1.13 \text{ g/cm}^3$  under aerobic conditions<sup>[58]</sup>. When using water-soluble organic C as the explicative variable, Urakawa *et al.* found a significant correlation to Net  $N_{min}$  ( $r = 0.34$ ) but not gross  $N_{min}$  ( $r = 0.15$ )<sup>[19]</sup>.  $N_0$  was found to correlate with the fine-particle organic matter C ( $r = 0.64$ ) but not with coarse-particle organic matter C ( $r = 0.33$ )<sup>[8]</sup>.

Measurements of organic matter in the soils determined that Gross  $N_{min}$  was not correlated with free amino acids in the soil<sup>[59]</sup>.  $N_0$  was positively correlated with soluble carbs ( $r = 0.71$ ) and total carbs ( $r = 0.72$ ) in soils<sup>[8]</sup>, while  $N_{min}$  is negatively correlated with lignin in soil ( $r^2 = 0.7$ ) as lignin is hard to decompose. Morecroft *et al.* found that the significance of the relation of  $N_{min}$  to loss of ignition was dependent on the site and date of sampling<sup>[26]</sup>. Since N is released from organic matter into inorganic molecules in the soil through the process of mineralization, it is assumed that there is a correlation between organic matter and  $N_{min}$ , and there are several ways to measure organic matter, but the most common approach is by measuring soil organic carbon (SOC). Our research yielded 33 records from 19 research papers, of which 60.6% showed a significant correlation between the variables. The most common results found a positive correlation with SOC with  $N_{min}^{[6,30,35,63,97]}$  or  $N_0^{[8,30,33,70,91]}$  as the dependent variable, while Zhang *et al.* found a significant negative correlation between SOC and  $N_{min}$  ( $r = -0.555$ ). They inferred the negative correlation due to enhancement in relative C limitations since compounds containing C and N are utilized by a larger fraction, or organic N is not retained but mineralized<sup>[59]</sup>. Some studies found no correlation between SOC



and  $N_{min}$  [36,51,62], which can be related to the negative correlations found between  $N_{min}$  and C:N ratio in the organic matter [6,96]. No correlation with  $N_0$  [8] indicated that the chemical composition of the organic matter affects  $N_{min}$ . This was confirmed by Mehnaz *et al.*, who found significant differences in  $N_{min}$  when SOC came from different sources (glucose, oxalic acid, and phenol as the SOC sources) [22]. Hu *et al.* found a significant correlation of SOC with TN ( $r = 0.887$ ) but not with inorganic N ( $r = 0.401$ ), again confirming a separation of what is available in organic matter and whether N is mineralized or not [44]. A study found that the relationship between  $N_{min}$  and SOC may depend on the time of year during which it is measured. They found a significant correlation between these variables in August and September but not in May, June, or July [21]. Their results coincide with the findings of Hou *et al.*, who found an interactive effect of the organic matter and the time of the year on the  $N_{min}$  rate [40]. Five studies included analyses correlating soil organic N with  $N_{min}$  or availability, finding them to be positively correlated [8,19,30,92,96], but only found a discrepancy. They related mineralizable N in the soil and crop residues to be used as amendments to soil organic N. However, while it was found to be positively correlated with the crop residues ( $r = 0.591$ ), there was no significant correlation when testing the soil without the crop residues.

### Soil microbiota

Independent variables describing soil microbiota as explicative variables to  $N_{min}$  or availability were obtained from 17 papers, with a total of 50 records using 14 different variables related to microbial activity, abundance, or specific information with chemical or community composition. Of the 14 variables, only microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and the presence of Nitrifier Bacteria were found with inconsistent results, while the rest demonstrated consistent results. MBN is the most common variable describing microbiota (28% of recorded microbiota data), followed by MBC (22%). All except four of the relational data found MBN to be positively correlated with  $N_{min}$  [6,51,76,98]. Li *et al.* found that the correlation was significant in the global data, and when separated, they confirmed the correlation for every ecosystem except wetlands ( $P = 0.13$ ) [1]. A study conducted in a headwater catchment of the Taizi River in China, a place with a temperate monsoon climate, reported no significant correlation between  $N_{min}$  and MBN [36]. Conversely, a study conducted in a subtropical monsoon climate showed that MBN was positively correlated with inorganic N but not with total N [44]. Similarly, Zhang *et al.* found no significant correlation between  $N_{min}$  and MBN or MBC [59]. It is important to mention that this was the only study that did not find a significant correlation with MBC in a laboratory study that included different water content treatments that have a 90% water-holding capacity (WHC) level and a low oxygen level (1%). Also, it has been reported that microbial growth reaches its maximum at 33% WHC [60]. A higher WHC level changes the microcosms to a suboxic regime, resulting in a decline in potential enzyme activities and slowing metabolic activity and microbial growth. However, N mineralization persists and increases due to a decrease in N immobilization, resulting in a separation between MBN and  $N_{min}$ . Such a separation can most likely happen in any place where the soil gets saturated with water, like watersheds, wetlands, paddies or over-irrigated croplands. When using MBC as an explanatory variable, only one study found it unrelated to N mineralization [59]. The rest found it to be positively correlated ( $P < 0.05$ ) with  $N_{min}$  [1,6,36,76], TN, and inorganic N [44].

Microbial abundance measured as active biomass [93] or as phospholipid fatty acids abundance [10] was found to be positively correlated with  $N_{min}$  ( $r = 0.991$  and  $r^2 = 0.43$ , respectively). The density of ammonifier bacteria was correlated with  $N_{min}$  [53], whereas no correlation was found when using the density of nitrifier bacteria. Another study related the abundance of nitrifying bacteria to Organic N, Inorganic N, and N losses [42]. However, only found it significantly related to inorganic N ( $P = 0.0084$ ), showing a relation to mineralization but not to the availability of organic matter or leaching.

With respect to microbial activity, respiration was found to be positively correlated with  $N_0$ <sup>[99]</sup>, and urease activity was correlated with the  $N_{min}$  rate with an exponential relationship<sup>[40]</sup>. But, when several enzymes were condensed into one variable and analyzed by a path analysis<sup>[76]</sup> or a structural equation model<sup>[98]</sup>, a negative correlation was found with  $N_{min}$ . Several studies have used specific information about the microbiota to relate it to N cycling. Zhang found no relation between the presence of fungi (pathogenic, non-pathogenic, or mixed) and  $N_{min}$  or  $N_{nit}$  rates<sup>[95]</sup>. But, when Vazquez *et al.* included a Fungi: Bacteria ratio in the path analysis, they found it negatively correlated with Net  $N_{min}$  ( $r = -0.16$ ), indicating that bacteria have a higher mineralization power than fungi<sup>[76]</sup>. When using the C:N ratio in the microbiota as an independent variable, two studies found a negative correlation with  $N_{min}$ <sup>[6,59]</sup>. One study compared treatments with a chitinolytic fungus, a chitinolytic bacterium, and two nitrifying bacteria in different combinations. The results ( $P < 0.05$ ) indicate that not only does the presence of certain organisms promote mineralization, but the combination of the organisms can affect mineralization due to the interactions within the microbial community, including inhibitions and competition.

## CONCLUSION

Our wide exploration of state of the art for  $N_{min}$  process showed that soil and environmental factors evaluated under different circumstances resulted in inconsistencies in the amount of N mineralized. The major factors that have a tremendous and variable effect on  $N_{min}$  are identified. These factors include soil microbial biomass, organic matter, C:N ratio, aeration/ $O_2$ - $CO_2$ , cation and anion exchange, soluble salts content, pH, moisture, temperature, textural composition, soil management focused on organic residues, plant roots effect, type of vegetation, and special conditions such as snow density, soil erosion, topography, and climate characteristics on a particular ecosystem.

The topographic and climatic *environmental factors* provide the base environment where mineralization processes occur. It is advisable to consider the experimental condition (field, lab, or greenhouse) to determine if their influence is accurately reflected in the results and that microclimates can differ from an area's general climate. The details of the *ecosystem* and *vegetation* explain the source of the organic matter, its diversity, and the nutrient proportions that compose it. Hence, it is essential to consider the combined effects of climate due to its significant impact, as shown by some of the results. The composition of the plant and proportions of tough and soft tissues are better predictors for mineralization than species diversity since they are directly correlated with organic matter lability. *Management* can affect all aspects of soil, from climate (irrigation) and ecosystem (crop species) to soil properties (density, pH) and organic matter (with weeding and amendments), and indirectly the microbiota. As a result, different management techniques will affect mineralization differently. Soil *physicochemical properties* create the microclimate in which the process of mineralization occurs. It also affects mineralization indirectly, as it influences the principal participants in the process, the *organic matter* that contains the nutrients and the *microorganisms* that liberate them through their metabolism. The classification we used grouped similar factors and separated them from the outside of the process, ranging from the general outside climate to the direct participants essential in mineralization, such as the organic matter and microorganisms.

For this reason, we have concluded that both research goal scenarios, the development of a general prediction model for the  $N_{min}$  process and the development of a specific equation for local conditions, have a limitation for use in crop production. Therefore, we deemed that generating a prediction model for  $N_{min}$  that can support decisions for soil and crop management in the face of global climate change would be helpful. This model must cover significative independent variables and a range of conditions for a productive region, uncultivated forest, or grassland.

## Research prospects

Considering the findings in the present paper, future  $N_{\min}$  modeling studies could include a comparison of models under the circumstances that create differences in the results of correlational relationships among variables, like comparing models for different ecosystems. Such an approach will improve our understanding of the nuances of soil processes and incorporate soil management strategies into production and conservation efforts.

## DECLARATIONS

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### Authors' contributions

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Mendoza-Carreón G, Flores-Márgez JP, Osuna-Avila P, Sanogo S  
Performed data acquisition, as well as provided administrative, technical, and material support: Mendoza-Carreón G and Flores-Márgez JP

### Availability of data and materials

Not applicable.

### Financial support and sponsorship

None.

### Conflicts of interest

All authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

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