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A Typological Concept to Predict the Nitrogen Release from Organic Fertilizers in Farming Systems

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Abstract: The prediction of nitrogen (N) mineralization or immobilization in organic fertilizers is an important tool to optimize fertilizer use, especially in intensive agricultural systems. Our aim was to derive a model to predict the N mineralization/immobilization from readily available information on the properties of organic fertilizers in farming practice. On the basis of a literature review, a characterization of organic fertilizers was performed, revealing a large variance in fertilizer properties within the defined categories and subcategories. A partial linear model was derived and used for the prediction of N mineralization/immobilization based on the type of fertilizer and the carbon (C) to organic nitrogen (N_{org}) ratio. Depending on the previously defined category, a strong mineralization (e.g., plant- and animal-based commercial fertilizers) or a predominant immobilization (e.g., compost and slurries) was detected. For a total of seven main categories and their subcategories, individual models were developed. This work shows that the mineralization properties of organic fertilizers can be sufficiently predicted through a simple classification into a fertilizer category and through the C to N_{org} ratio.

Keywords: organic fertilizer; nitrogen release; organic farming; C to organic N ratio

1. Introduction

In conventional and organic crop systems, the management of plant nutrition and soil fertility is based on the supply of inorganic and organic nutrients. Organic fertilizers and crop residues are important nutrient sources for plants in sustainable crop systems [1]. This applies above all to the plant available N (sum of NO_3–N, NO_2–N, and NH_4–N), which is usually the limiting nutrient in intensive plant cultivation systems [2].

Depending on the origin of the fertilizer, the proportion of N available to plants in organic fertilizers varies greatly [3]. The inorganic N content (mainly NH_4–N) in organic fertilizers ranges from 0% of total N in keratin-based fertilizers to 70% and more in liquid organic fertilizers. A considerable part of the N is present in an organically bound form. The organic matter of fertilizers is first mineralized by soil microorganisms, and thus is converted into an inorganic plant-available form. Consequently, the amount of plant-available N from organic fertilizers in the soil varies in the first period (month within growing period) after application [3,4]. This fluctuation occurs within the same fertilizer class (e.g., keratin-based fertilizers), but also between fertilizer groups, such as manures, slurries, or commercial fertilizers [3,5]. Predicting N mineralization primarily from the organically bound N fraction in organic fertilizers is one of the most important objectives for improving the efficiency of N use in agricultural cultivation systems [4,6,7]. This knowledge is crucial because of a lack of information on the amount of plant-available N that is mineralized within the cultivation period.

To predict the N mineralization of organic fertilizers depending on their composition, several approaches have been pursued in the past, all using different quality parameters [7–14].

However, many of the relevant parameters in the models are not part of the standard analyses of organic fertilizers in agricultural practice and are not always useful to predict N mineralization [15]. Most of the models for the N release from organic fertilizer in the first year after application are based on the assumption of different organic pools, which are mineralized at different rates. Previous publications have suggested that knowledge about the different pools of organic matter cannot be meaningful without detailed knowledge of the soil properties and quality indices of organic fertilizers and climatic conditions [9,16]. Therefore, prediction of the nutrient supply from organic fertilizers is often not reliable [17,18]. A further reason is the large variety of organic fertilizers, some of which differ greatly in nutrient content, composition, application method [19], and quality [20], thus making individual fertilizer models considerably more difficult to investigate.

Previous researchers have investigated the N release properties of different classes of organic fertilizers, such as plant residues [2], manure [4,21,22], and waste water from the food industry [23] individually as a function of the C to N ratio. The authors pointed out several factors that influenced the properties of the N supply. They agreed that the C to N or the C to N_{org} ratio of the organic fertilizer was the main factor influencing the net N release within the first months after application under constant incubation conditions. Environmental conditions, such as soil water content, soil texture, and soil temperature, have an important effect on the nitrogen release from organic fertilizers [24–26]. A further factor that impacts the nitrogen release from organic fertilizers is the application method, for example, mixing or surface application [19]. It is also clear that biochemical composition plays an important role in improving the prediction of the N supply of organic fertilizers. The biochemical composition of organic fertilizers, such as neutral detergent fiber content, water-soluble N content, and lignin or polyphenol content, can have a significant influence on net N mineralization [2,27,28]. The proportion of this easily degradable pool in an organic fertilizer depends on several properties, such as chemical composition and environmental conditions. Several publications have pointed out that the short-term N supply of inorganic N significantly depended on the ratio of organic carbon to organic nitrogen (C to N_{org}) or the ratio of organic carbon to nitrogen (C to N) in organic fertilizers [4,8,29]. Organic fertilizers with a C to N_{org} ratio below 20–30 lead to the mineralization of the nutrient N, while higher C to N_{org} ratios lead to N immobilization followed by a mineralization or immobilization process [2,30]. When the C to N_{org} ratio in organic fertilizers is higher than 30, the risk of immobilization of inorganic N increases, which is associated with a decrease in plant-available N. In such a case, the risk of yield loss significantly increases the economic risks, as the expected fertilizing effect may not occur. The main environmental factors influencing the degradation of organic matter under arable farming conditions are soil water content and soil temperature [28]. However, knowledge of the factors that predict organic fertilizer mineralization is not sufficient to explain net N mineralization [17].

In agricultural practice, the analysis of several quality parameters of organic fertilizers involves a great deal of effort, which makes the establishment of analytical methods to measure potential N release difficult. Due to the high complexity, it is not realistic to identify better relationships than the relationship of C to N for predicting the N mineralization of organic matter [31]. To solve this problem, Morvan, et al. [31] characterized slurry based on several quality characteristics. After characterization, they successfully classified organic fertilizers in terms of composition criteria and C and N mineralization properties. Their work implied that organic fertilizers of the same origin should follow a comparable mineralization course. Therefore, it should be possible to predict N release from organic fertilizers within organic fertilizer classes and subclasses. Therefore, a broad spectrum of different fertilizer variations can be evaluated based on the literature data from incubation experiments.

First, we wanted to provide an overview on the nutrient contents and mineralization properties of organic fertilizers in agricultural practice, from which it was possible to carry out an investigation of the short-term mineralization of organic fertilizers and plant residues according to a classification with data that were usually available in agricultural practice. From this, a tool was developed, which was able to provide recommendations for a wide range of applications of organic fertilizers in agricultural practice. We further established that the relationship between the N release and C to N_{org} ratio of organic fertilizers could be predicted by the type and processing of the fertilizer. Therefore, categorization into simple main groups and subgroups of organic fertilizers would likely improve the prediction of N input from organic fertilizers using standard parameters without complex analysis of the applied material.

2. Materials and Methods

2.1. Data Selection

In order to achieve an overview of the mineralization behavior as a function of the measurable quality parameters of organic fertilizers in the soil, a literature review was carried out. The selected studies on N supply with organic fertilizers and plant residues were carefully checked and investigated with ISI Web of Knowledge (https://apps.webofknowledge.com) and Google Scholar (https://scholar.google.com). The search was conducted according to the following five criteria to select suitable data: (1) To avoid random environmental effects such as tensile stress or temperatures below 5 °C, and to ensure a distinction between different N sources, only incubation studies without plant N uptake were selected. (2) Mineralization time history studies should have more than three sampling times. (3) To avoid atypical conditions, publications should provide sufficient information on organic fertilizers such as C and N content, soil properties such as texture, and experimental conditions such as temperature. (4) For the calculation of net N mineralization, the control without fertilization should be considered or included in the results of the expression of the net N mineralization/immobilization. (5) In order to avoid the probability of atypical incubation conditions, some studies were excluded that presented mineralization curves that differed significantly from the expected values, for example, if net N mineralization release rates were unexplainably much higher than 1 g g^{-1} N_{org}, which implied an additional N release from soil organic matter.

Following this selection procedure, 98 studies with 835 observations representing the N mineralization kinetics of soil organic matter were used for data analysis. The soil moisture in the experiments was adjusted between 40% and 80% of the maximum soil water holding or field capacity, known as the optimal for organic matter mineralization. The soil was incubated in glass and plastic jars or plastic bags under aerobic conditions. The documented amount of soil for the experiment ranged between 80 and 2500 g, but not each experiment offered this information. The incubation temperatures in the studies ranged between 5 and 35 °C. Organic fertilizers were mixed homogenously with the soil in each study. The applied amount of fertilizer N ranged between 10 and 1500 mg N kg^{-1}. Because of a lack of information, not all required information was available in each study. However, incubation temperature, applied fertilizer, and soil water content were documented in each study. The soil types varied widely among the studies and ranged from sandy to clay soil. However, a soil group classification was performed due to LUFA soil classification because of different documentation styles.

The evaluation and later model development were based on a classification of organic fertilizers mainly by type of raw material and processing. The properties of the processing steps before their application in the field, such as composting or anaerobic processing, were used as further classification criteria. Table 1 shows the seven classes and 27 subclasses used in the present study. The main classes were formed in a practical way from commercial fertilizers and farm manures, to which compost was also assigned. The commercial fertilizers were mainly residues from the industrial processes of food production or seed-based fertilizers. Green manure was defined as fresh plant material, while farmyard manure was split into solid manure from ruminants (cattle/sheep manure) and swine, as well as solid manure from poultry and slurry. Finally, compost was prescribed as material composted at temperatures of approximately 60 °C. The subclasses were defined as subgroups of the main classes. Biosolids are defined as the solid residues of municipal wastewater treatment [32].

Table 1. Overview of the main groups (bold text) and corresponding subgroups. The numbers in parentheses represent the number of observations.

Commercial Organic Fertilizers of Plant Origin (170)	**Solid Farmyard Manures (67)**
Plant-based mixture (26)	Swine manure (14)
Legume meal (77)	Biosolid (20)
Production residues (22)	Cattle/sheep manure (33)
Seed meal (19)	
Vinasse (26)	**Poultry manures (114)**
	Poultry manure (98)
	Poultry manure-based mixture (16)
Commercial organic fertilizers of animal origin (83)	**Slurries (100)**
Hair, horn, and feather residues (47)	Biogas slurry (32)
Meat bone and fish meal (21)	Wastewater (21)
Blood meal (15)	Swine slurry (9)
	Cattle slurry (38)
Green manures (204)	**Composts (83)**
Non-legume green manure (126)	Plant compost (20)
Legume green manure (66)	Manure compost (52)
Green manure mixture (12)	Compost mixture (6)
	Fungi biomass manure (5)

2.2. Determination of net N Mineralization from Organic Fertilizers

Data describing the soil properties and the experimental set-up were taken from text passages or tables from the analyzed publications. N release was extracted from the figures with the R (GNU) package "pixmap" (Team 2014) to obtain the values from the diagrams. To calculate the daily cumulative net release from the organic fertilizers in the soil/fertilizer mixtures, the following formula was used:

$$N_m = \frac{\left(Nmin_{sf} - Nmin_s\right)}{N_{org}} \tag{1}$$

where N_m is the net N mineralized or immobilized from the N_{org} of the organic fertilizer; $Nmin_{sf}$ represents the sum of NH_4–N and NO_3–N in the soil/fertilizer mixture during the incubation of the soil/organic fertilizer mixture; amd $Nmin_s$ describes the sum of NH_4–N and NO_3–N of the soil without the addition of an organic fertilizer. The organic N content of the organic fertilizer (N_{org}) was calculated as the difference between total N and fertilizer inorganic N (NH_4–N and NO_3–N).

A first-order kinetic model was used to represent the course of N mineralization/immobilization from the organic fertilizer:

$$N_r = N_0 * (1 - \ exp(-k \cdot \ w(T) \cdot t)) \tag{2}$$

where N_r is the amount of net mineralized/immobilized N_{org}, as a sum of NO_3–N and NH_4–N released at time t after application; N_0 represents the maximum potential mineralization/immobilization rate of added N_{org}. If N_r and N_0 are positive, mineralization processes dominate, whereas negative values describe immobilization processes. The parameter k represents the first-order rate constant expressed as thermal time after cooperation $[°\mathrm{Cd}]^{-1}$ at T_{opt}; *w(T)* is a temperature adjustment calculated according to Thornley [33] and De Neve [34], where T_{opt}, T_{min}, and T_{max} are 35, −5, and 45 °C, respectively; T is the temperature of the incubation experiment.

$$\begin{aligned} w(T) &= \frac{(T-T_{min})^{q(T)} \cdot (T_{max}-T)}{\left(T_{opt}-T_{min}\right)^{q(T)} \cdot \left(T_{max}-T_{opt}\right)} \\ q(T) &= \frac{\left(T_{opt}-T_{min}\right)}{\left(T_{max}-T_{opt}\right)} \end{aligned} \tag{3}$$

After calculating the values for N_0 and k for each N mineralization/immobilization observation, the relationships between the ratio of C to N and C to N_{org} were analyzed by a stepwise rank correlation analysis. Due to a strong significant correlation between N_0 and the C to N ratio (data not shown), the C to N_{org} ratio was selected for the model approach.

Thereafter, the representation of N_0 was conducted using a partial linear model of organic changes within the first 150 days after the application of organic fertilizer as follows:

$$\begin{gathered} region1(CN_{org}) = (y1 \times (x2 - t) + y2 \times (CN_{org} - x1))/(x2 - x1) \\ region2(CN_{org}) = (y2 \times (x3 - t) + y3 \times (CN_{org} - x2))/(x3 - x2) \\ region3(CN_{org}) = (y3 \times (x4 - t) + y4 \times (CN_{org} - x3))/(x4 - x3) \\ N_0 = if(CN_{org} \leq x2; region1(CN_{org}); if(CN_{org} \leq x3; region2(CN_{org}); region3(CN_{org})))) \end{gathered} \tag{4}$$

where $x1$ to $x4$ are the limits of the linear models that represent the C to N_{org} ratio (CN_{org} of organic fertilizer), and $y1$ to $y4$ represent the net N mineralization of organic N (g g^{-1} fertilizer N_{org}). The parameterization was performed by the R-package "optimx." To avoid unrealistic results, all linear parts of the partial linear model should show a negative increase due to a general negative relationship between the N mineralization and the C to N_{org} ratio in organic fertilizer. This requirement had no relevant effect on the model error.

2.3. Statistics

For the root mean squared error (RMSE), the mean absolute error (AEM) was used to describe the performance of the model. The influence of the quality parameters on the maximum release rate of organic fertilizers was tested by stepwise linear regression analysis with the R package "olsrr." To test the effect of soil type, a classification of the presented soil information according LUFA was conducted previously.

$$AEM = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i) \tag{5}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{6}$$

3. Results

The contents of total N_{org} in the selected main categories and subcategories of fertilizers are shown in Figure 1. Compared with the organic C content, the N content within most of the fertilizer groups had a wide range (Figures 1 and 2). Only the materials that are mainly decomposed by microorganisms in the preparation process (i.e., manure, compost, and slurry) and commercial organic fertilizers have a low variation in N_{org} content. The commercial organic fertilizers of animal origin are characterized by the highest N_{org} contents among the main groups, mostly above 90 g N_{org} kg^{-1} of dry matter (DM). The production residues, legume meals, plant-based mixtures, and vinasse follow with values between approximately 40 and 80 g N_{org} kg^{-1} DM. Interestingly, leguminous green fertilizers show only slightly lower N_{org} contents than the commercial fertilizers of plant origin. The lowest N_{org} contents are documented for the already fermented or composted fertilizers, i.e., cattle/swine/sheep manures, manure compost, plant compost, and fungi biomass manure. The N_{org} contents of the subgroups hardly differ from those of the corresponding main groups.

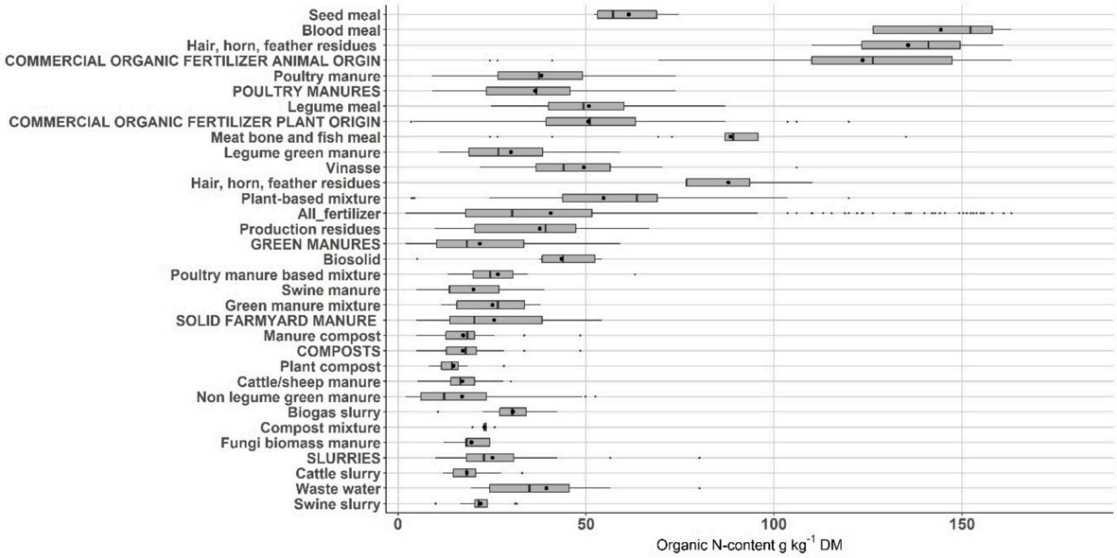

Figure 1. Boxplot of organic N content in the fertilizer main groups (capital letters) and subgroups. The circles are the means and the stripes are the medians of the observations.

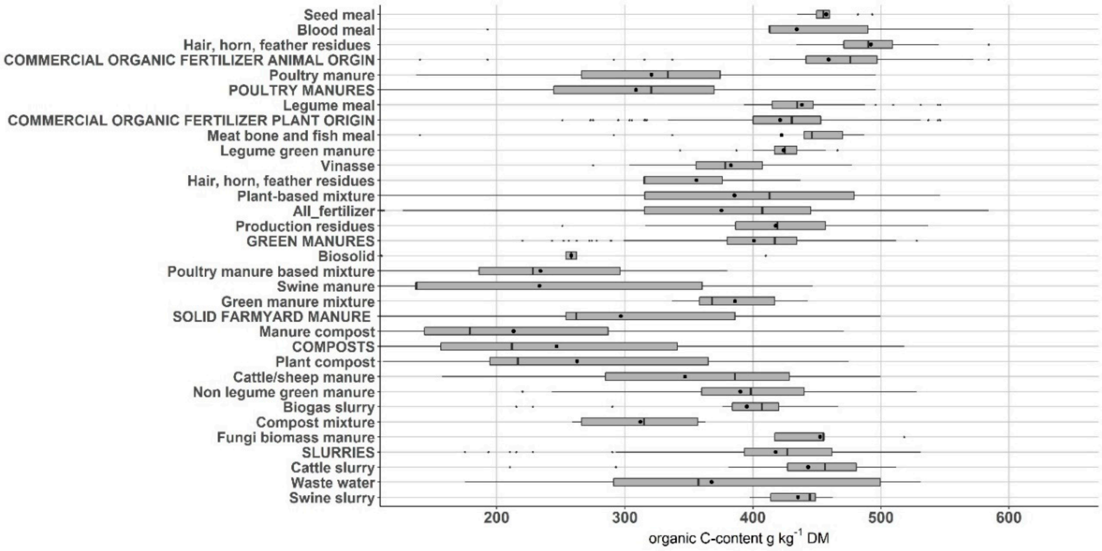

Figure 2. Boxplot of organic C in the fertilizer main groups (capital letters) and subgroups. The circles are means and the stripes are the medians of the observations.

The C to N_{org} ratio for most of the commercial organic fertilizers of animal origin is typically characterized by a value below 10 (Figure 3), for example, keratin-based fertilizers (mean C to N_{org} = 3.7), legume meals (mean C to N_{org} = 9.1), and Vinasse (mean C to N_{org} = 8.9). In contrast, the C to N_{org} ratio is higher for most plant-based commercial organic fertilizers, and also the range of variation shows an increase (Figure 3). Manures, green manures, and wastewater should be highlighted here, as their ranges of variation are amongst the highest.

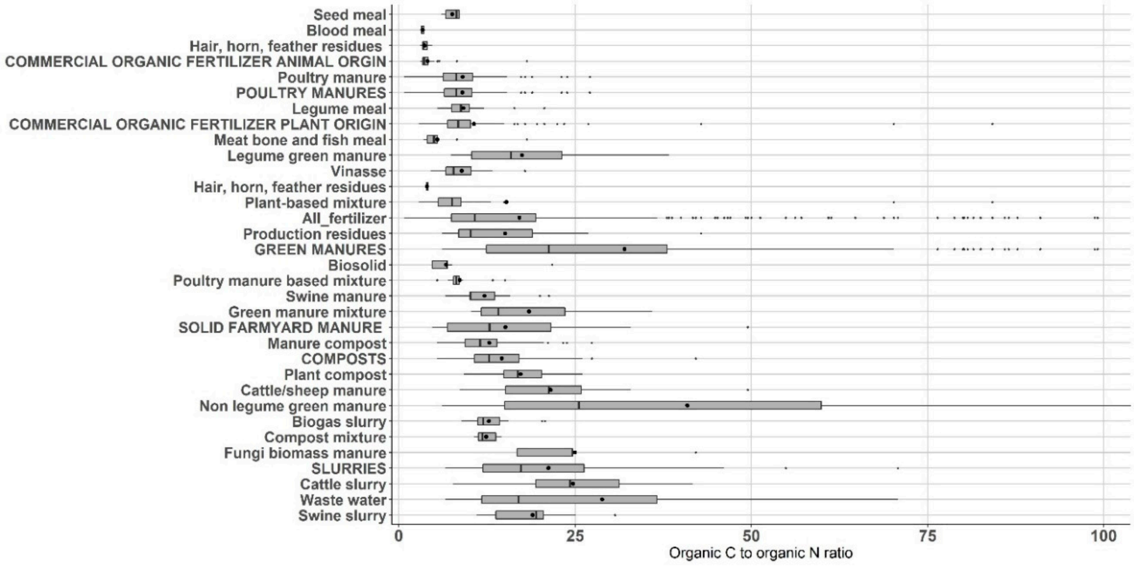

Figure 3. Boxplot of organic C to organic N ratio in the fertilizer main groups (capital letters) and subgroups. The circles are means and the stripes are the medians of the observations.

To determine the release of N_{org} (N_0) in the first 150 days after manure addition, a simple exponential model was used to interpret the mineralization course for each study. The calculated N_0 from organic fertilizer varies widely within most organic alteration groups (Figure 4). In addition, according to N_0, the range of variation of the N mineralization or immobilization among the organic fertilizer groups was high. The mean N_0 was highest in the main groups of commercial fertilizers of animal origin, poultry manure, and commercial fertilizers of plant origin. Here, on average, 50%, 41%, and 40%, respectively, of the added N_{org} was released within the first month after application.

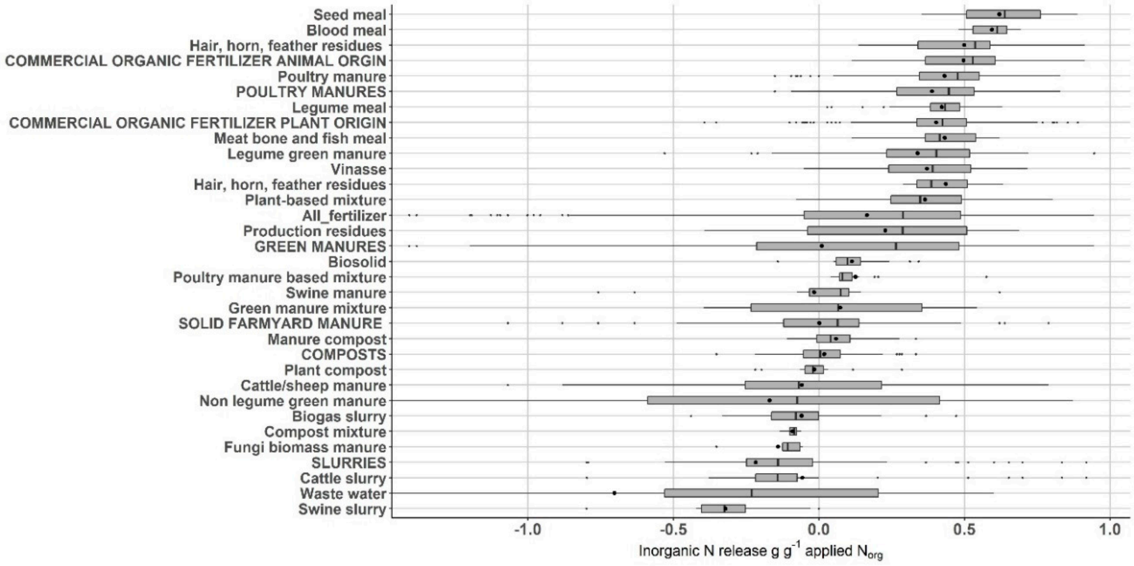

Figure 4. Boxplot of potential inorganic N release (N_0) of the fertilizer main groups (capital letters) and subgroups. The circles are the means and the stripes are the medians of the observations.

Arranged by main groups, the release properties of the organic fertilizers decrease from commercial fertilizers of animal origin > poultry manure > commercial fertilizers of plant origin > green manures > composts > slurries. In particular, seed meal, blood meal, and hair, horn and feather residues are effective organic fertilizers, with a mean N_{org} release of approximately 50% within the first 150 days after application. Conversely, the N_{org} fraction in solid farmyard manures and composts tend to immobilize inorganic N in the soil (Figure 4). The N release from composts and solid farmyard manures shows low mineralization to moderate immobilization. In general, the subgroups follow the same pattern as their corresponding main groups. Poultry manure, however, has a similar mineralization pattern as the subgroups of the commercial fertilizers of animal origin and the commercial fertilizers of plant origin. Plant residues and wastewater show a strong immobilization up to a high mineralization rate of >50% of total N_{org} within the first 150 days. The variation of inorganic N release differs strongly within the subgroups (Figure 4). The highest immobilization was estimated after the application of wastewater and non-legume green manure, which reached up to −200%.

The mineralization rate constant (k) shows high variations among the main groups and subgroups (Figure 5). This is most pronounced for plant-based commercial organic fertilizers and composts. Green and solid farmyard manures display a smaller range and a similar mean k of approximately 0.35. In most publications, there was no evidence of a relationship between the C_{org} and N content, suggesting that k is likely to be affected by temperature and quality indications not presented here.

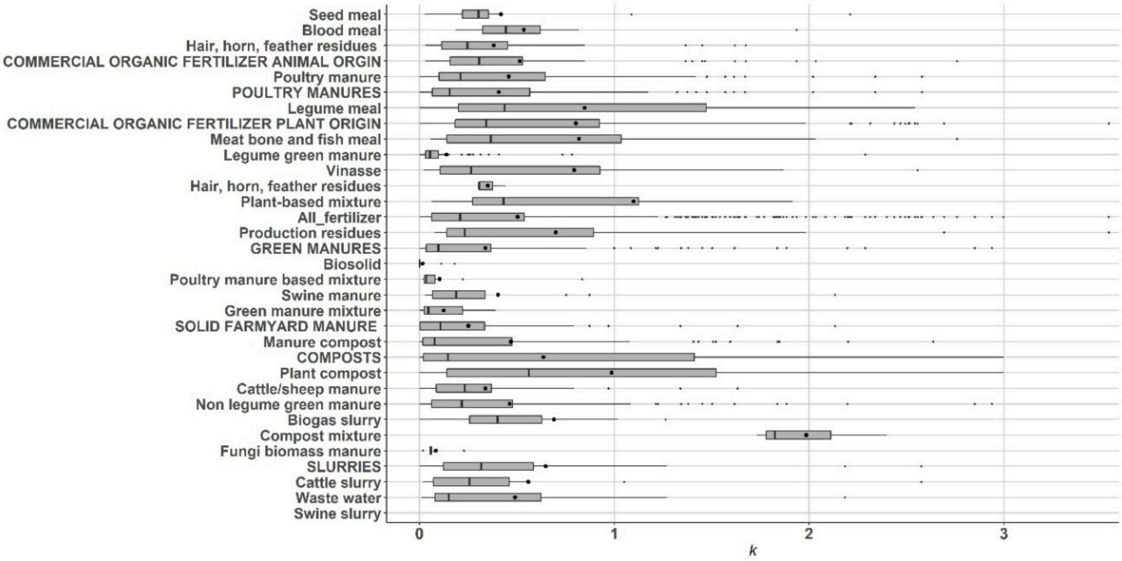

Figure 5. Boxplot of the mineralization rate constant k [°Cd]$^{-1}$ of the fertilizer main groups (capital letters) and subgroups. The circles are the means and the stripes are the medians of the observations.

By partial linear regression, a negative relationship between N_0 and the organic C to N_{org} emerged for the subclasses (Figures 6 and 7). Due to the very different progression of mineralization/immobilization within the solid farmyard manure group, poultry manure was excluded from this group and presented separately (Figure 6). Due to the chosen partial linear model, the main groups and subgroups of fertilizers follow predominantly the same partition pattern. The mineralization of fertilizers that only consist of a few components and feature a small C to N_{org} ratio, such as horn-based fertilizer, (hair, horn, and feather residues and keratin based mixtures) did not exhibit a significant correlation ($p > 0.05$) with the C to N_{org} ratio. The N mineralization within the different fertilizer main classes as a function of the C to N_{org} ratio generally showed different courses. The courses of the net mineralization for composts differed from most fertilizer categories (Figure 7). Even for composts with narrow C to N_{org} ratios, a low mineralization of approximately 5% of the total N_{org} or immobilization of mineral N was forecasted.

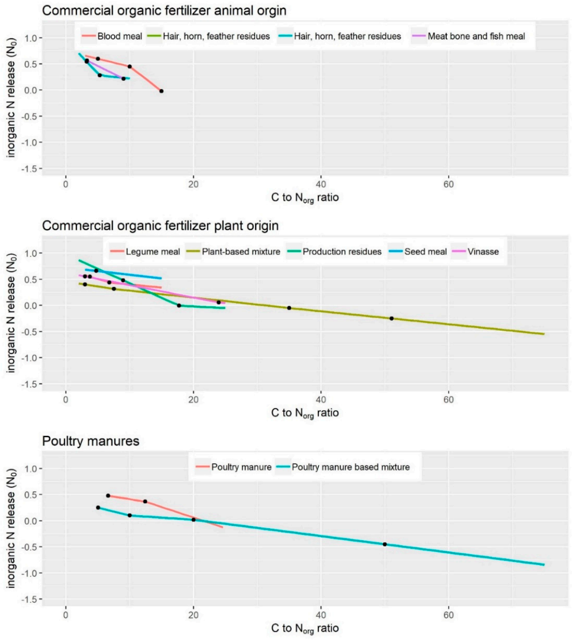

Figure 6. Dependency of potential inorganic N release within 150 days after organic fertilizer application on the fertilizer C to organic N ratio in different fertilizer classes.

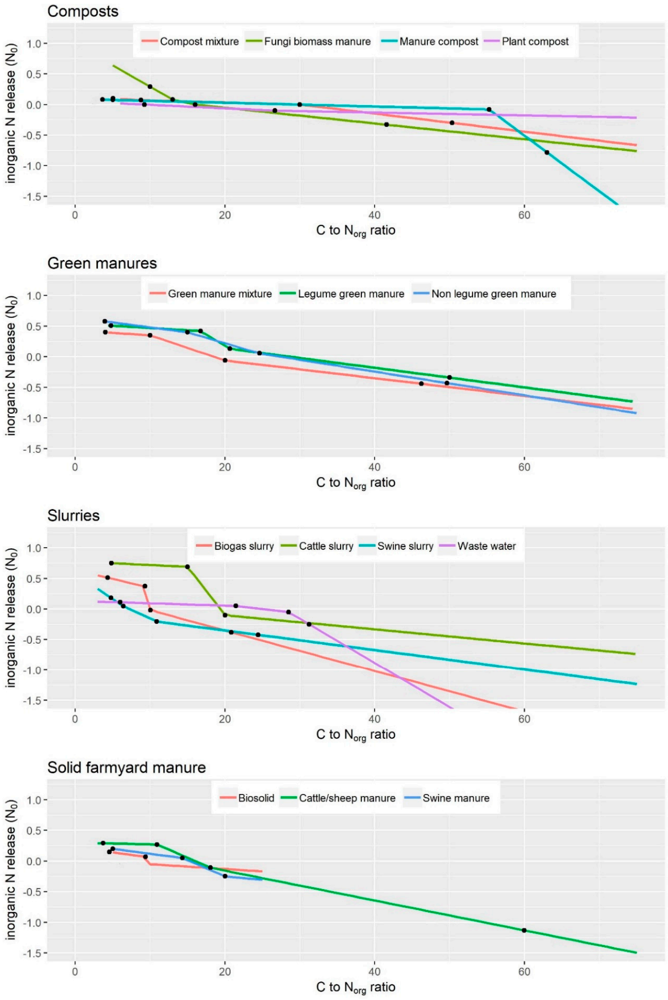

Figure 7. Dependency of potential inorganic N release within 150 days after organic fertilizer application on the fertilizer C to organic N ratio in different fertilizer classes.

The t- values of the stepwise linear regression analyses of N_0 on the C to N and C to N_{org} ratios are −6.4 and −25.1, respectively (Tables 2 and 3). No significant relationship was found between k and the quality parameters instead of significant temperature effects (Table 4).

Table 2. Forward stepwise linear regression analysis of N_0 for the parameters C to N ratio, N content of the fertilizer, incubation temperature, and soil class.

	Beta	SE	std. Beta	t	*p*
(Intercept)	0.383	0.247		1.55	NS
N content	0.211	0.089	0.164	2.363	<0.05
C to N ratio	−0.625	0.094	−0.451	−6.648	<0.05
Inkubation temperature	0.004	0.002	0.059	1.883	NS
Soil class (LUFA)	0.016	0.011	0.044	1.432	NS

Table 3. Forward stepwise linear regression analysis of N_0 for the parameters C to N_{org} ratio, N content of the fertilizer, incubation temperature, and soil class.

	Beta	SE	std. Beta	t	*p*
(Intercept)	1.298	0.047		27.459	<0.05
C to Norg ratio	−1.049	0.042	−0.66	−25.125	<0.05

Table 4. Forward stepwise linear regression analysis of k for the parameters C to N ratio, C to N_{org} ratio, N content of the fertilizer, moisture (in % maximum water holding capacity), incubation temperature, and soil class.

	Beta	SE	std. Beta	t	*p*
(Intercept)	0.004	0.062		0.059	NS
Incubation temperature	0.012	0.002	0.194	4.91	<0.05
Soil class (LUFA)	−0.016	0.012	−0.054	−1.374	NS

The model-dependent RMSE of the prediction of the mineralization rate and the correlation coefficients of the prediction show the lowest values, with approximately 0.10 and 0.14 g g $^{-1}$ N_{org} for composts and commercial organic fertilizers, respectively. Higher values for the RMSE of above 0.21 and 0.27 g g $^{-1}$ N_{org} are measurable in the main groups of manures and commercial fertilizers from plant material (Table 5). The plant residues by far, however, show the highest RMSE. A differentiation into subgroups resulted in a clear improvement of the prediction for most cases; however, this is not adaptable for all subgroups.

Table 5. Model statistics of the prediction quality of the observed data. Root mean squared error (RMSE), absolute error of mean (AEM), and bias in g g $^{-1}$ N_{org}.

Name	*n*	RMSE	AEM	Bias
Biogas slurry	32	0.131	0.085	0.017
Non-legume green manure	126	0.43	0.306	0.185
Hair, horn, and feather residues	47	0.186	0.138	0.035
Legume meal	77	0.094	0.068	0.009
Manure-based mixture	16	0.11	0.081	0.012
Meat bone and fish meal	21	0.097	0.072	0.009
Manure compost	52	0.097	0.076	0.009
Plant-based mixture	26	0.251	0.185	0.063
Blood meal	15	0.087	0.068	0.008
Plant compost	20	0.104	0.066	0.011

Table 5. *Cont.*

Name	*n*	RMSE	AEM	Bias
Poultry manure	98	0.187	0.135	0.035
Production residues	22	0.16	0.125	0.026
Seed meal	19	0.163	0.144	0.027
Swine manure	14	0.234	0.149	0.055
Swine slurry	9	0.192	0.142	0.037
Vinasse	26	0.192	0.153	0.037
Wastewater	21	0.393	0.323	0.155
Biosolid	20	0.081	0.065	0.007
Cattle slurry	38	0.226	0.138	0.051
Cattle/sheep manure	33	0.331	0.24	0.11
Compost mixture	6	0.152	0.149	0.023
Fungi biomass manure	5	0.034	0.027	0.001
Legume green manure	66	0.183	0.146	0.033
Green manure mixture	12	0.144	0.113	0.021

4. Discussion

The data obtained from this literature review confirmed that the realization of N supply in fertilizer management with organic fertilizers depends on the type of fertilizer. After the application of organic fertilizer, the N_{org} has to be converted by soil microorganisms in order to become available to plants. Thus, the amount of plant-available N released from organic fertilizers is generally lower than the amount of plant-available N after the application of synthetic fertilizers. Depending on the treatment and composition of the fertilizer, the proportion of inorganic N hardly differed within commercial organic fertilizers of animal and plant origins. The assigned fertilizers of the respective group featured a high N content, and thus revealed a low C to N ratio. Hence, commercial organic fertilizers of animal and plant origins provided a high amount of plant available N [35–38]. The N fractions in most commercial organic fertilizers are mainly comprised of uniform and relatively pure substances, such as keratin, blood proteins, or plant proteins. Those proteins are readily degradable, and therefore are rapidly mineralized by the soil microbial community [39]. Therefore, the high net N mineralization rates observed for both groups can be explained by the very high proportion of readily available N_{org} for microbial conversion in the soil [40].

It is noteworthy that, at a similar net N release of approximately 40–50% (0.4–0.5 g g $N_{org}{}^{-1}$), the average C to N ratio of plant-based commercial organic fertilizers was higher than the C to N ratio of those of animal origin. It is possible that readily degradable proteins of both groups are converted into inorganic N during the first 150 days after application, whereas the long-chain organic compartments present in plant-based commercial organic fertilizers are mineralized much slower. In commercial organic fertilizers of plant origin, these are usually components of stable compartments with a high C to N ratio, such as lignin and polysaccharides, which partly explain the higher total C to N ratio in the material. Polysaccharides such as hemicellulose and cellulose in legumes [41] and increased amounts of aromatic compounds in production waste [42] also have a decelerating influence on the mineralization process. Differences in short-term N release could probably be explained by an inhibitory effect expressed in the hemicellulose, polyphenol to N ratio, lignin, or lignin and polyphenol to N ratio [39,43]. However, due to the lack of detailed information on the content of lignin, hemicellulose, or polyphenolic substances in most publications, it was not possible to further investigate the correlations between these quality parameters and the course of N release.

The above-mentioned quality parameters also occurred in varying proportions in green manure fertilizers, which consisted of different shares of shoots, leaves, and seeds. As shown in this literature overview, other studies have also demonstrated a high variation of the C to N_{org} ratio within this main group and a highly negative correlation of the C to N_{org} ratio with the net N mineralization [27,44]. The critical C to N_{org} ratio for the net N immobilization was 26 for green manures, as previously observed by Trinsoutrot et al. [45]. With regard to their immobilization behavior, green manure fertilizers behaved analogously to the group of commercial fertilizers of plant origin.

A strong negative relationship between the C to N_{org} ratio and the net N mineralization was shown for most of the other fertilizer classes (Figures 6 and 7). The critical C to N_{org} ratio varied only to a small extent, whether or not the negative relationship was significantly pronounced. However, this depended mostly on the variation of the C to N_{org} ratio within the fertilizer classes. This could be observed after the application of keratin-based fertilizers, whose mineralization behavior showed no significant dependence on the C to N_{org} ratio due to a small variance in the C to N ratio (Figure 6). There could be a link between the mineralizable fractions of commercial organic fertilizer of animal origin and solid farmyard manures from ruminants, an assumption derived from the course of the partial linear model (Figures 6 and 7) of both fertilizer classes. The N mineralization of commercial fertilizers of animal origin and solid farmyard manures (excluding poultry manures) followed a similar pattern. Similarities in the protein composition, breakdown products, or composition between the two fertilizer groups could be related to the fact that both fertilizer groups are of mammal origin (with the exception of feather meal). The divergence in the course of the net N mineralization of poultry manures was probably related to their high proportion of urea. Similar to both groups of commercial fertilizers, poultry manures had high levels of readily microbial available N, and their low content of fiber could accelerate the N mineralization [30] as compared with manures of different animal origin.

The main reason for the difference in the net N mineralization among poultry manures and the remaining solid farmyard manures could be in the concentration of uric acid and total N or denitrification losses [46,47]. Uric acid is rapidly hydrolyzed to urea, and then presented in plant-available form [48,49]. The content of uric acid that was converted into inorganic N before application could have had an influence on the proportion of N_{org} released from the fertilizer. The remaining solid farmyard manures were characterized by a very low net mineralization within the first year of application. This was in line with several publications that have investigated the N availability of swine, cattle, sheep/goat, and horse manures [4,50,51]. In the composting process, inorganic N is reduced and the stabilization of N_{org} is increased. Our results also indicated that the immobilization of N_{org} outweighed the N mineralization immediately after the application of manure [4].

In contrast to solid farmyard manures, a high share of inorganic N in the total N pool characterized the group of liquid fertilizers. In contrast, the net N mineralization from the N_{org} content of these fertilizers was low. Our data implied that the N_{org} content of the manures induced the immobilization of inorganic soil N by the microbial soil community. This was supported by the wide C to N_{org} ratios, which were associated with immobilization in the other fertilizer groups. Moreover, it could not be excluded that gaseous N losses via N_2, N_2O, and NH_3 influenced the results. This was consistent with several publications where a net N immobilization was observed in the first 21 weeks after the addition of biogas or solid farmyard manures [52–55]. Other authors have also pointed out a reduction in net N utilization associated with an increased proportion of fibers in source materials or diets [56]. Approximately 25% of NH_4–N in manure was immobilized within the first two weeks after application by the soil microbial community or by the mineral phase of the soil [53,57]. This could also explain the negative inorganic N availability and the relationship between the C to N_{org} ratio of organic change and N release. Compost is an organic fertilizer that has been stabilized by microorganisms during the composting process [58]. During the composting process, the organic N was converted into stabilized organic forms, while the easily degradable fraction decreased. Therefore, the converted stabilized N_{org} generally showed a very low release of inorganic N in this evaluation.

The mineralization rate constants showed a high variation over most organic fertilizer classes and subclasses. No general statements about the relationship between fertilizer quality and mineralization rate could be derived from this work. However, it could be stated that in most of the evaluated incubation experiments, a fast release rate was observed. The influence of the soil water content, which was found in many publications [59,60], could not be assessed in this work, because the water content was always adjusted to the optimum required for the microbial activity. The particle size of the fertilizer could also impact the mineralization rate constant. For example, the processing of organic fertilizer into flour increased the fertilizer's particle surface area. This enlargement of access for the microbial activity resulted in a quicker mineralization of the particles [39,59]. However, no clear evidence of a dependence of processing on k was found in this work (Table 4).

In some publications, the first day for the determination of net N mineralization was probably chosen too late. This could have resulted in an underestimation of the mineralization rate constant, as the maximum cumulative release could already have occurred between the first and second measurement dates. Due to the high variation of incubation temperatures and in relation to the mostly missing information on ingredients, an effect of multiple sugars and aromatic compounds on the mineralization or immobilization rate could not be excluded, but was also not quantified by our data. The main factor for the prediction of the mineralization rate constant in this data compilation seemed to be the soil temperature. Other influencing factors, such as the impact of the composition of the organic fertilizer on the mineralization rate constant, the C to N_{org} ratio, or the N content were not applicable here. The results presented here were taken as the mean values of the temperature-dependent mineralization rate for our model. In contrast to the mineralization rates presented in this paper, here again, the range of N mineralization was arguable.

In previous articles, the variation of the inorganic N availability from commercial organic fertilizers of animal origin was explained by the incubation temperature [61], the immobilization of inorganic N in the presence of high inorganic N contents in the soil [62], or by soil texture effects [63]. On the contrary, the correlation analysis carried out in this work suggested that the main factors for the mineralization rate could be described by the C to N_{org} ratio of the fertilizer. It should be noted that all plant residues caused net N mineralization if the incubation period was extended [2]. This implied that the prediction of the net N immobilization through a one-pool model did not project the dynamics for a long-term consideration of net N mineralization from organic fertilizers. In theory, a two-pool model seems to be more suitable. However, the development of a goal-oriented model requires standardized incubation conditions with a high temporal resolution. Better results from the compiled data were obtained using a one-pool model, which could be due to the various incubation conditions in the investigated experiments. Furthermore, the predictions of net N immobilization with the one-pool model were more robust and led to a better prediction than with several pool models [62,64]. As suggested by [63], the remineralization of immobilized N was not easy to determine, as it was influenced by several factors that were not available in agricultural practice. The timing and extent of remineralization seemed to depend on the soil type, as well as on the soil temperature [11], which was not quantifiable in this work.

Our results emphasized that the type and the processing of organic fertilizers were largely responsible for the N composition and mineralization properties. Thus, untreated organic fertilizers such as keratin fertilizers or legume flours showed the highest average release rates, whereas composting or anaerobic/aerobic storage resulted in a reduction of the net N mineralization. The main factor for the determination of the net mineralization was, in addition to processing, the C to N_{org} ratio (Table 2). Within most of the fertilizer categories used in this publication, an individual correlation with the C to N_{org} ratio was evident to determine the course of the N mineralization/immobilization. Hence, components such as hemicelluloses affected these dynamics [27,31]. The reasons for the variation of the C to N ratio within the fertilizer groups were manifold and usually reflected the proportion of proteins or multiple sugars (i.e., lignin, cellulose, or hemicellulose). Many of these properties affected the composition of the processed organic fertilizer. Here, however, the duration, intensity, and environmental conditions during composting or fermentation were also decisive [58].

The classification into subclasses did not have an inherent positive effect on the prediction of net N mineralization. In addition, the prediction of net N mineralization for the six defined main classes showed acceptable results. However, the determined prediction error was relatively high, which could also be due to the varying quality of the evaluated incubation experiments. Nonetheless, it was clear that a classification of organic fertilizers by the type of raw material and processing was a useful tool to predict the N release with respect to generally available quality parameters. This was in line with other publications that highlighted the classification of organic fertilizers to be a useful tool to improve the prediction of net N mineralization [31,65]. This was not the case for the prediction of the mineralization rate constant. Here, the results of the work did not show any relationships that were dependent on the fertilizer class. A classification is recommended if no detailed information about the composition of the regarded fertilizers or their quality parameters are available. For a suitable classification, describing the original material (e.g., feedstock) or consistency can be sufficient, to get a first hint about the N release properties from organic fertilizers. This may allow more robust and generalized predictions of the N-release of organic fertilizers in the future. Thus, the use of organic fertilization can be optimized, resulting in a reduction in N losses. Implemented into a model, the data can be an important contribution to the decision-making process for the application of new organic fertilizers. Nevertheless, the results presented here should also be viewed with caution, as the model errors are too high to allow a precise prediction of organic fertilizer N release. Therefore, standardized incubation conditions regarding temperature and resolution of measurements during incubation should be defined separately for each fertilizer category. The standardization of the incubation conditions could significantly reduce the error of the prediction.

Due to their high release rate of inorganic N, the use of commercial organic fertilizers of animal origin meets the demand of plant species with high N requirements, such as most Brassica in vegetable production systems. Since their N to P ratio is relatively high, they qualify as a suitable fertilization option in intensive organic production systems. These systems are usually characterized by a high surplus of P resulting in a high P accumulation in the soil. It should be noted, however, that these fertilizers are by-products from mostly intensive animal production. Their carbon footprint and greenhouse gas potential [66] are usually associated with negative environmental impacts. Therefore, the environmental disadvantages of animal production systems should be taken into account when applying keratin-based fertilizers. In Europe, there are already strict regulations that limit the application of blood- and bone-based fertilizers [67]. The associated risks of using these fertilizers are mostly related to hygienic concerns. Commercial organic fertilizers of plant origin have also been proven to be highly effective fertilizers; however, an influence on plant protection and crop rotation must be taken into account. For example, the cultivation of legumes and/or Brassica in the same area is associated with cultivation breaks of three to four years. Techniques such as catch and carry or transfer mulch could complement successful fertilizing strategies here. These organic substances can be used specifically for organic fertilization, for example, from multi-crop green crops or catch crops. If a growth stage with the lowest possible C to N_{org} ratio is defined, the organic fertilization can be optimized. Due to a favorable carbon footprint and good availability of N, green manure fertilizers from plant residues should gain more importance in intensive production systems [68].

Since only small amounts of organic N are obtained for uptake from composted organic material (i.e., manure and compost) into the plant in the first year of application [69], these organic fertilizers are only suitable for soil improvement, and thus represent a fertilizer class with long-term effectiveness. The same applies to solid farmyard manures. Here, however, an increased risk of leaching during the crop-free period under continental climate conditions must be pointed out. Therefore, fertilizers with a long-term effect on the high nutrient requirements of vegetable crops must be regarded as critical in intensive vegetable growing. The use of liquid fertilizers in intensive vegetable growing is mostly limited to preplanting periods by legal restrictions, and therefore their application should be considered with regard to application timing and avoidance of gaseous N losses.

The developed models were incorporated into the calculation software "N-Expert" [70], which could be used to calculate the N demand in open field planting systems.

5. Conclusions

The C to N_{org} ratio in organic fertilizers, in combination with the conducted fertilizer classification, seems to be a good indicator for predicting the N availability from organic substances. It was clearly shown that, with some exceptions, the mineralization of N_{org} can be sufficiently predicted by the origin, treatment, and formulation of the respective group. In this context, organic commercial fertilizers of animal origin with a fast and high release rate, as well as plant-derived commercial fertilizers and fertilizers of plant production residues (e.g., vinasse), should be highlighted as efficient organic fertilizers. However, the influence of the soil properties on immobilization cannot be evaluated by the current data. Our literature research reveals that the N availability for the first year after application can be predicted to a satisfying degree. By means of categorization, it is possible to develop a model relevant for agricultural practice with reduced input requirements for gaining essential information on fertilizer quality. To reduce the prediction error, a standardized test design for incubation experiments is crucial.

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