Optimising organic nitrogen fertilisation in horticultural growing media

Patrice Cannavo, Moammed Benbrahim, Matthieu Valé, Sophie Bresch, Marie-Anne Joussemet, Olivier Yzebe, Sylvie Recous, René Guénon

Optimising organic nitrogen fertilisation in horticultural growing media

Patrice CANNAVO[1], Moammed BENBRAHIM[2], Matthieu VALE [3], Sophie BRESCH [4], Marie-Anne JOUSSEMET[5], Olivier YZEBE[4], Sylvie RECOUS[6], René GUENON[1]

[1]Institut Agro, EPHOR, 49000, Angers, France

[2]RITTMO Agroenvironnement, ZA Biopôle, 37 rue de Herrlisheim, CS 80023, CEDEX, 68025 Colmar, France

[3]AUREA AGROSCIENCES, 45160 Ardon, France

[4]CDHR Centre-Val de Loire, Domaine de Cornay, 45590 Saint-Cyr-en-Val, France

[5]Est Horticole, 28 rue du Chêne, 88700 Roville-aux-Chênes, France

[6]University of Reims Champagne Ardenne, INRAE, FARE, UMR A 614, 51100 Reims, France

Correspondence : patrice.cannavo@institut-agro.fr

Abstract

In order to be able to predict the nitrogen mineralisation from organic fertilisers in soilless growing media, it is necessary to identify the factors influencing mineralisation and to model their effects. To date, there is no model for the mineralisation of organic nitrogen applied to soilless growing media. The aim of the work carried out in the CASDAR OptiFaz project was to propose a predictive tool for reasoning organic fertilisation in soilless conditions, taking into account temperature and moisture, the physical, chemical and biological characteristics of the growing medium and organic fertilisers, and finally to assess the biological activity of growing medium-organic fertiliser mixtures. Based on incubations under controlled conditions on 4 growing media and 2 major commercial organic fertilisers, it was possible to model the mineralisation kinetics of organic nitrogen. In the future, the specific behaviour of the growing media suggests that the range of fertiliser-growing medium combinations studied should be extended to make the models more robust. Finally, the role of the plant and its effects on the mineralisation of organic nitrogen will need to be characterised and modelled.

Key words: temperature, moisture, mineralisation rate, modelling

Introduction

Consumers are concerned about the quality of the food they eat and the environmental impact of its production. Demand for organic farming products has increased significantly in recent years (Jerkebring, 2015). Organic fertilisers represent a sustainable alternative to synthetic mineral fertilisers. In conventional soilless production, plants grow in a limited volume of organic growing medium, which means they have limited buffering capacity (in terms of water, temperature and nutrients in particular). These growing media are biologically stable because their organic matter is resistant to biodegradation. The introduction of organic fertilisers requires practices to be adapted, as the organic fertilisers must first be mineralised by the growing medium's microbiota before being assimilated by the plant. A satisfactory level of microbial activity in growing media is therefore essential to achieve this objective (Caldwell, 2005).

Such specific features mean that the horticultural profession needs to be able to offer tools for predicting mineralised nitrogen, adapted to the diversity of fertilisers and organic growing media available on the market. In particular, accurate simulation of nitrogen mineralisation in growing media is crucial to improving nitrogen management in order to i) match fertiliser timing and doses with crop nitrogen demand, ii) maximise economic efficiency and iii) minimise mineral nitrogen losses to the environment. Consequently, the challenge for organic horticulture is to achieve better knowledge of nitrogen availability after organic fertilisation, for optimal synchronisation of nitrogen availability with crop nitrogen demand (Burnett et al. 2016; Tittarelli et al. 2017).

At present, there is a clear lack of reference data on the mineralisation dynamics of organic fertilisers in soilless crops. We hypothesised that certain formalisms established to predict the mineralisation of organic nitrogen in soils could be used and adapted in the context of soilless crops (Ma and Shaffer, 2001; Nicolardot et al., 2001).

The aim of the OptiFaz project, supported by Astredhor, was to develop tools for analysing and managing organic fertilisation adapted to soilless conditions, and to support manufacturers, technicians and growers in their practices. More specifically, the aim was to (1) characterise and model the nitrogen mineralisation dynamics of soilless organic fertilisers for a number of fertilisers and growing media, (2) develop field indicators for use by growers to manage organic fertilisation under *in situ* conditions, and (3) propose a predictive tool for reasoning about organic fertilisation in soilless conditions. This project was carried out in the absence of plants.

The project partners were technical institutes (Astredhor, ITAB), experimental stations (CDHRC, Est Horticole, GRAB, CIVAM Bio), a soil and growing medium analysis laboratory (Auréa AgroSciences), a technology resource centre (RITTMO Agroenvironnement), a research unit (EPHor unit, Institut Agro Rennes-Angers) and a horticulture and landscape school at Roville-aux-Chênes.

1. Materials and methods

1.1 Selecting fertiliser/substrate combinations

On the basis of a database of the characteristics of commercial fertilisers and growing media, a selection of fertiliser-growing medium pairs was made in order to study the various factors thought to have an impact on mineralisation: (1) for growing media, the crop use, constituents and particle size; (2) for fertilisers, the origin (animal, vegetable, mixed), manufacturing process (composting, granulation) and particle size. The compositions of the growing media and fertilisers chosen are shown in tables 1 and 2.

Table 1: Physico-chemical properties of growing media S1, S2, S3 and S4

	S1	**S2**	**S3**	**S4**
Professional use	**Flowering plants and bedding plants**	**Market garden plants in plugs or trays**	**Tree and shrub container**	**Market garden plants in plugs or trays**
Bulk density ($g\ cm^{-3}$) [1]	0,18	0,20	0,12	0,18
Total porosity (v/v) [2]	89,1	88,3	92,0	88,0
Water availability (v/v) [3]	0,38	0,41	0,23	0,40
Air availability (v/v) [4]	0,17	0,03	0,47	0,04
pH water [5]	6,8	6,7	7,3	6,5
Electrical conductivity ($mS\ cm^{-1}$) [6]	0,7	0,7	0,6	0,6
Organic matter ($g\ kg^{-1}$) [7]	687,3	690,6	908,5	712,6
Organic N ($g\ kg^{-1}$)	11,1	11,1	6,9	13,1
C-to-N ratio	30,9	31,0	65,9	27,2

[1,2,3,4] AFNOR (2000a), [5] AFNOR (2000b), [6] AFNOR (1998), [7] determined at 550°C, 7 h

Table 2: Composition of organic fertilisers F1 (of animal origin), F2 (of plant origin)

	F1	F2
Organic matter (g kg^{-1})	559,5	636,7
Total C (g kg^{-1})	279,8	318,4
Organic N (g kg^{-1})	59,5	54,1
Total N (g kg^{-1})	67,4	55,1
Total P (mg kg^{-1})	35,4	18,6
Total K (mg kg^{-1})	52,3	40,8
C-to-N ratio	3,8	5,1

1.2 Growing medium incubation and analysis methods

Experiments were carried out under controlled conditions to establish the kinetics of organic nitrogen mineralisation in different fertiliser-growing media combinations. The incubations were carried out by our partner Aurea AgroSciences. The four growing media were incubated at four temperatures (4, 20, 28 and 40°C) and three matric potentials (-3.2, -10.0 and -31.6 kPa corresponding to pF1.5, pF2.0 and pF2.5, respectively), with or without the addition of fertiliser, in the dark and in the absence of plants. Matric potential characterises the energetic state of water in a soil. It corresponds to the pressure required to extract water from the soil. The more negative the value, the greater the suction required to extract water from the soil by plants, and the lower the moisture content of the growing media. Destructive samples were used to extract and measure N-NH_4^+ and N-NO_3^- after 3, 7, 14, 28 and 49 days. Organic fertiliser was applied at a rate of 55 g N kg^{-1} growing media dry weight basis. The amount of fertiliser applied was calculated on the basis of growers' usual practices (200 g N fertiliser m^{-3} growing media). N-NH_4^+ and N-NO_3^- were extracted and measured with de-ionised water (1:1.5 vol.) for 1 h. Concentrations were determined by colorimetry using a continuous flow analyser (Skalar Analytical). Three replicates were prepared per modality. Nitrifying bacteria were quantified as follows: total nucleic acids were extracted from growing media samples using a Qiagen DNeasy PowerSoil kit (Cat No./ID: 12888-100), followed by a quantitative polymerase chain reaction using primers 968 R and 1401 R for total bacteria and primers amoA-1F and amoA-2R for nitrifying bacteria.

1.3 Modelling the mineralisation of organic nitrogen

1.3.1 Kinetic model of 1^er^ order

Two modelling approaches were used. Firstly, the kinetics of net nitrogen mineralisation were modelled using a first-order kinetics model. This formalism was chosen because it is widely used to model the mineralisation of organic matter in soils (Cannavo et al., 2008). The prediction of net nitrogen mineralisation was calculated as follows:

$$N = A \times [1 - \exp(-K \times JN)] \qquad (1)$$

Where N is the predicted amount of mineralised N (expressed as % organic N applied), A (%) is the maximum percentage of mineralised organic nitrogen, K (j^{-1}) is the organic nitrogen mineralisation rate , and JN is the time, expressed in standardised days calculated as follows:

$$JN = t \times f(T) \times f(H) \qquad (2)$$

Where t is the incubation time (days), f(T) and f(H) the temperature and moisture functions, respectively.

This model was calibrated at T=20°C and pF2, i.e. the conditions for which the amplitude of mineralised nitrogen was highest, for all incubation data and for each growing medium, without distinction of fertiliser type (Cannavo et al., 2022).

1.3.2 Statistical model

Secondly, a statistical model was used: it consists in establishing a multivariate equation based on a few variables that can easily be used by growing medium and fertiliser producers. The multivariate model is as follows:

$$N=\alpha \times N_{Fert} + \beta \times N_{init} + \gamma \times JN \quad (3)$$

Where N_{Fert} is the N fertiliser content applied (mg N kg^{-1}), N_{init} is the initial N content in the growing medium (mg N kg^{-1}),α andβ are adjusted parameters.

The model was calibrated on 2/3 of the incubation database with the 4 growing media, the 2 fertilisers at all measurement dates during incubation (n=1235, with random selection). It was tested on the remaining 1/3 of the database (n=625).

1.3.3 Validation of models on independent data acquired in situ at partner experimental stations

The two models were tested on mineral nitrogen monitoring data under real greenhouse conditions, acquired under different French climatic conditions (Table 3), on the same growing media-fertiliser pairs studied in incubation and without plants. Table 3 shows the different experimental conditions. Experiments 1 and 2 were set up at the Est Horticole station (longitude 6°60' W, latitude 48°39' N), experiment 3 at the Astredhor Loire Bretagne STEPP station (longitude -2°71' W, latitude 48°50' N), experiment 4 at the CDHRC station (longitude 1°97' W, latitude 48°83' N), experiments 5 and 6 at CIVAM Bio 66 (longitude 2°90' W, latitude 42°70' N), and experiments 7, 8 and 9 at the GRAB station (longitude 4°81' W, latitude 43°95' N).

Table 3: In situ experimental conditions

Experience (issue)	Growing medium	T min - T max (T avg)	N fertiliser applied mg N kg^{-1}	Intial N min growing medium mg N kg^{-1}	Number of observations
1	S1	8,0- 32,1 (19,2)	1218	268	5
2	S1	1,2 - 21,3 (7,9)	1589	269	10
3	S1	-0,1 - 27,3 (9,8)	1618	271	3
4	S3	4,2 - 42,3 (21,8)	1765	265	6
5	S2	5,8 - 26,1 (14,0)	777	411	4
6	S4	5,8 - 26,1 (14,0)	980	149	4
7	S2	10,9 - 41,7 (24,7)	1765	411	1
8	S4	10,9 - 41,7 (24,7)	1967	149	1
9	S2	6,3 - 30,2 (16,4)	1043	411	1

These trials were carried out under cover to avoid rain and the watering was controlled in a harmonised way, by controlling on threshold weights, between the 6 sites in order to limit nitrogen losses by leaching. Part of the trials was carried out without plant material to avoid taking samples from the plant, and the other part with plant material to validate the practices in terms of production quality. Air and growing medium temperatures were measured continuously and before each watering, the pots were weighed to assess growing medium water content. Successive determinations of mineral nitrogen (Nitrachek) in the growing medium were carried out at regular intervals (between 7 and 15 days depending on the crop) to assess the impact of variations in temperature and humidity on the mineralisation of organic nitrogen (Figure 1). Depending on the crop, the percolates were also collected in order to carry out a complete nitrogen balance.

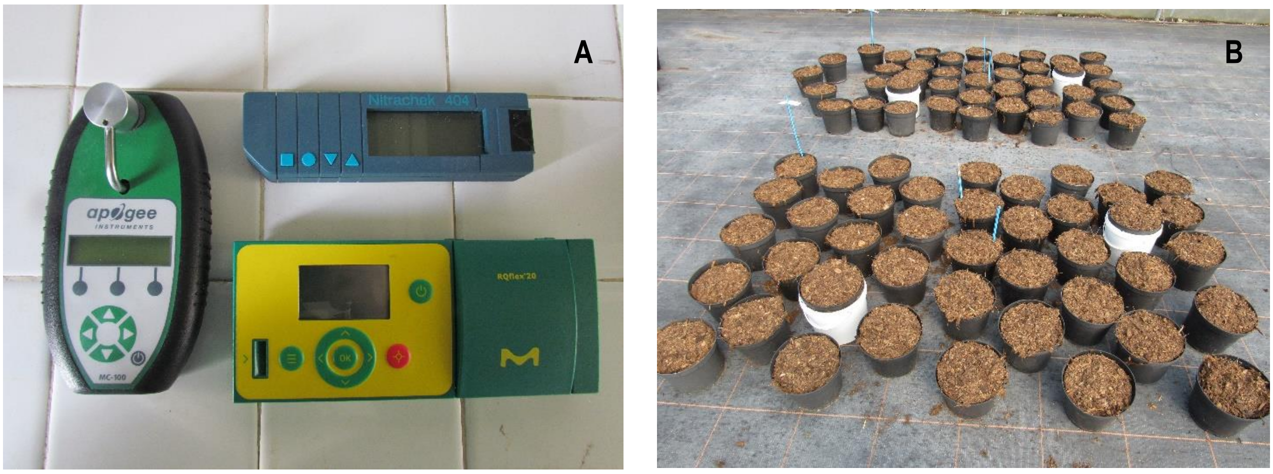

Figure 1: (A) Control tools used to monitor nitric nitrogen (Nitrachek®) and ammoniacal nitrogen (RQFlex®) levels in growing media and chlorophyll levels in leaves (MC-100 chlorophyll clamp), (B) In situ experimental set-up under cover with pots without plants.

2.Results

2.1 Dynamics of organic nitrogen mineralisation

The experimental incubation results were published by Cannavo et al (2022). An ANOVA analysis was carried out to identify the factors significantly involved in the mineralisation of organic nitrogen. The results show that mineral N production is dependent on growing medium type, humidity and temperature during incubation (first significant level of interaction). The type of fertiliser is not in the first level of significant interaction. The 2 fertilisers happen to have very similar biochemical compositions (table 2). They had, however, been chosen as *a priori* different because of their origins (plant vs. animal).

Net nitrogen mineralisation results from a combination of ammonium and nitrate production kinetics. Depending on the growing medium and the temperature and humidity conditions, these kinetics are quite varied. The effect of growing medium type on net N mineralisation is shown in Figure 2, and the kinetics presented correspond to treatments under 'comfortable' humidity (pF2) and temperature (28°C) conditions for the micro-organisms. The net nitrogen mineralisation curves (figure 2A), expressed as a function of the nitrogen supplied by the fertiliser, are the sum of the production of NH_4^+ (figure 2B) and NO_3^- (figure 2C).

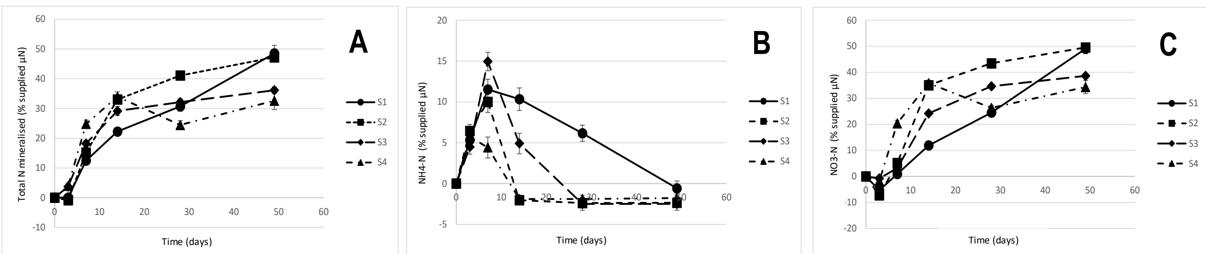

Figure 2 - Effect of growing medium on net nitrogen mineralisation: total mineral nitrogen (A), N-NH_4^+ (B), and N-NO_3^- (C), expressed as % of nitrogen supplied by fertiliser. Error bars represent standard error (n=3).

After 49 days, growing media S3 and S4 produced the least mineral nitrogen (32.7 and 36.7% of the nitrogen supplied). Growing media S1 and S2 converge towards the same value (49%). The kinetics of N-NH accumulation$_4^+$ are similar, with a peak observed after 3 days and a disappearance after 14 days. Growing media S4 had the lowest accumulation of N-NH_4^+, suggesting that the ammonitrifying micro-organisms were more active than in the other 3 growing media. During the first 3 days, a net decrease in nitrate was observed, corresponding to a phenomenon of net organisation of nitrogen, in growing media S1, S2 and S3 (Figure 2). One possible explanation is the C/N ratio of the growing medium, which is above 25, the threshold at which net organisation of nitrogen is possible.

The biological activity of the growing media was analysed by quantifying the genes of ammonium-oxidising bacteria. Figures 3 and 4 show the effect of temperature and incubation date on the richness of ammonitrifying bacteria in the growing media.

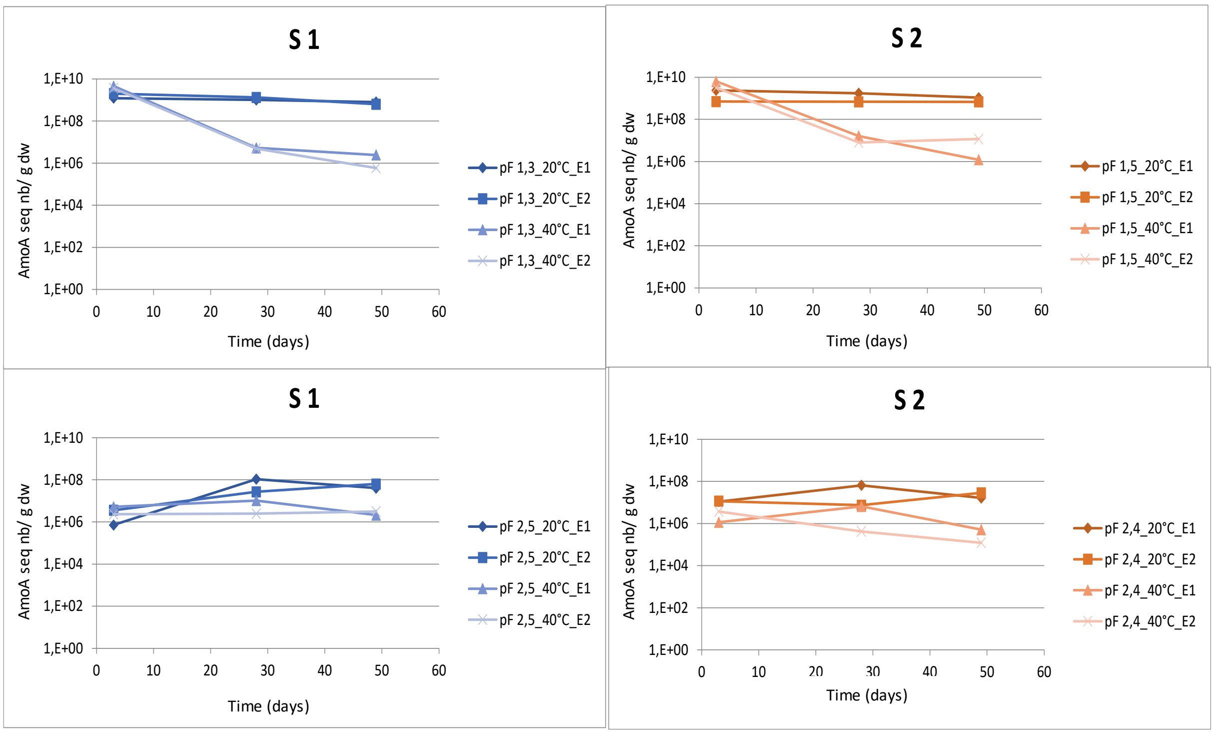

Figure 3: Changes in ammonitrifying microbial populations (carrying the amoA DNA sequence) as a function of incubation time under different humidity (pF) and temperature (°C) conditions in growing media S1 and S2.

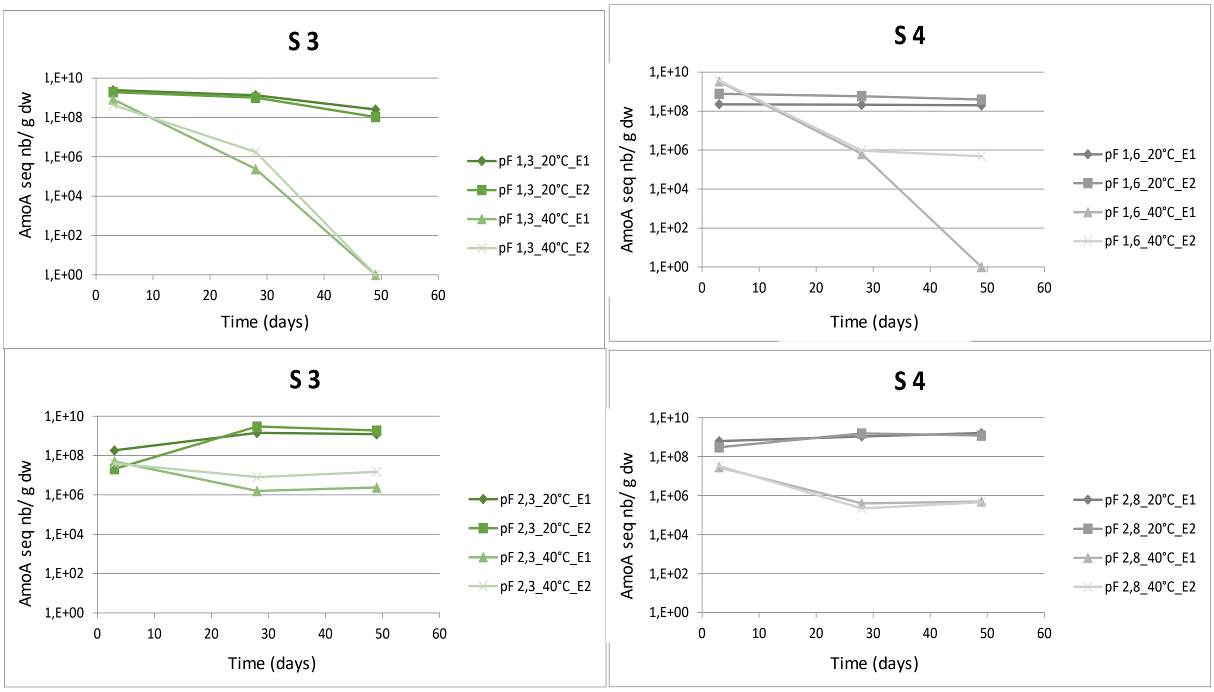

Figure 4: Changes in ammonitrifying microbial populations (carrying the amoA DNA sequence) as a function of incubation time under different humidity (pF) and temperature (°C) conditions in growing media S3 and S4.

These results show that ammonitrifying bacteria populations are sensitive to high temperatures. Indeed, for all growing media, increasing the incubation temperature to 40°C reduced the quantity of ammonitrifying bacteria. The level of sensitivity to temperature depends on the growing media and humidity. Similarly, the effect of humidity seems to be greater at medium temperatures (20°C), whereas at high temperatures (40°C), the effect of temperature is dominant and does not reveal an effect of humidity.

2.2 Modelling the mineralisation of organic nitrogen

A temperature action law was established for all growing media, at pF2, and by combining F1 and F2 fertilisers (Figure 5).

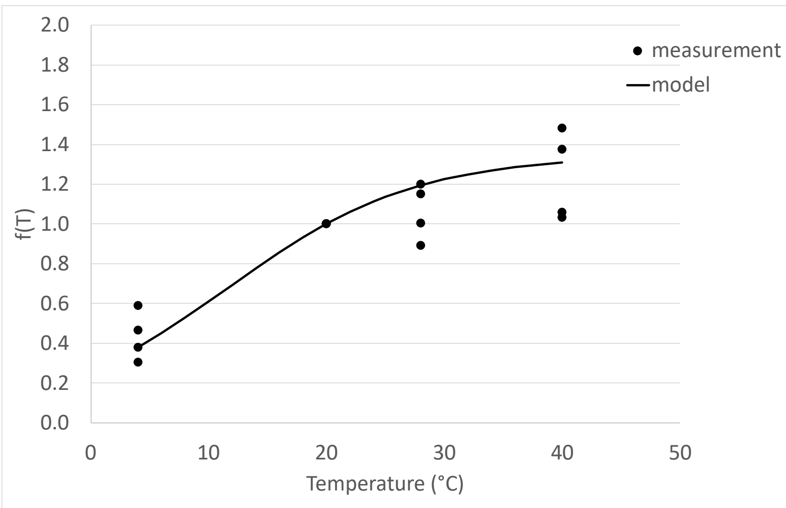

Figure 5: Response curve f(T) for mineralisation as a function of growing medium temperature. The f(T) factor describing this law of action is established for the 4 growing media, at pF2, and with 4 repetitions for each temperature (in total n=17).

The equation of the model, whose formalism is inspired by the STICS model (Brisson et al., 2008) to describe the mineralisation of soil organic matter, is written as follows (Cannavo et al., 2022):

$$f(T) = \frac{1.35}{1+2.12\times exp(-0.12\times T)} \qquad R^2 = 0.91, \text{ RMSE} = 0.14 \qquad (4)$$

The law of action of humidity, via the f(H) factor, could not be established. Different responses to humidity were observed for each growing medium. For this reason, the f(H) function was set at a value of 1 for the rest of the modelling work (which assumes no limitation of mineralisation by moisture content).

The modelling work is detailed in Cannavo et al., (2023), we summarize here the major results. The multivariate model is a statistical model that has no agronomic significance, but it enabled us to establish a robust model on a large dataset (n=1860) (Figure 6). Its strength also lies in its genericity, since it was designed on the basis of the mineralisation kinetics of the 4 growing media. To our knowledge, statistical modelling of this kind has never been applied to nitrogen mineralisation in growing media. To design this model, it was necessary to select a simple set of input parameters available to growing mediaproducers and fertiliser manufacturers (fertiliser nitrogen content, growing medium nitrogen content, growing medium temperature and moisture). We tried to improve this model by considering more parameters and in particular the physico-chemical parameters of growing media such as their water reserve, macroporosity, organic nitrogen content or C/N ratio. This did not improve the quality of the prediction. Table 4 shows the model calibration-validation parameters and performance (eq. (3)).

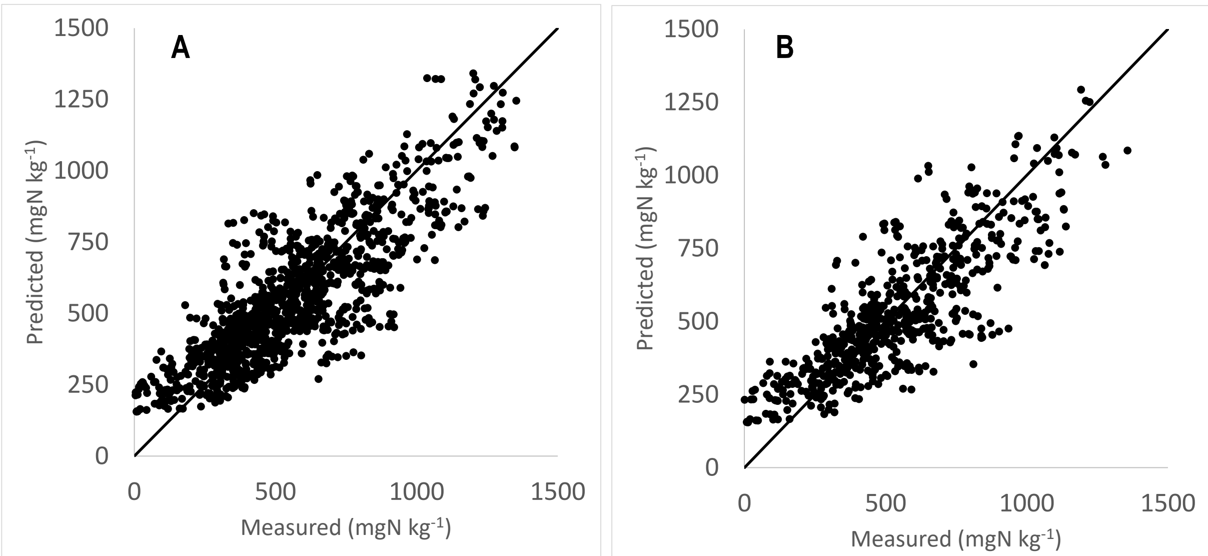

Figure 6: Calibration (A) and validation (B) of the multivariate model for predicting net nitrogen mineralisation.

Table 4: Validation parameters and statistical performance of the model

	α	β	γ	R^2	RMSE mg N kg^{-1} growing medium
Calibration n=1235	0,11	0,82	9,22	0,84	145,2
Validation n=625				0,83	145,5

The first-order kinetics model was developed for each growing medium and with fewer repetitions (n=6) than the multivariate model (Figure 7). However, its strength lies in the fact that it was able to identify agronomic parameters of interest, such as the mineralisation rate, a parameter used to assess the capacity of a growing medium to degrade an organic fertiliser. The four growing media were relatively similar in terms of physico-chemical properties, even though they were manufactured from different materials and for different crop objectives. The different mineralisation kinetics can be attributed to the microbial functioning of the growing media. The model calibration parameters are presented in Table 5. Calibration was good for the 4 growing media, with an R^2 of between 0.85 (S4) and 0.99 (S2), and a RMSE of between 1% (S1) and 10% (S2) (Table 2). The mineralisation rates, K, varied greatly with the type of growing medium, from K=0.013 to 0.178 d^{-1} for S1 and S4 respectively. The models were also tested at other temperatures and at pF2. Overall, the model reproduced well the experimental data , except for some extreme temperature conditions, namely at 4°C (S2, S3 and S4) and 40°C (S1 and S2), where the RMSEs were highest (results not shown).

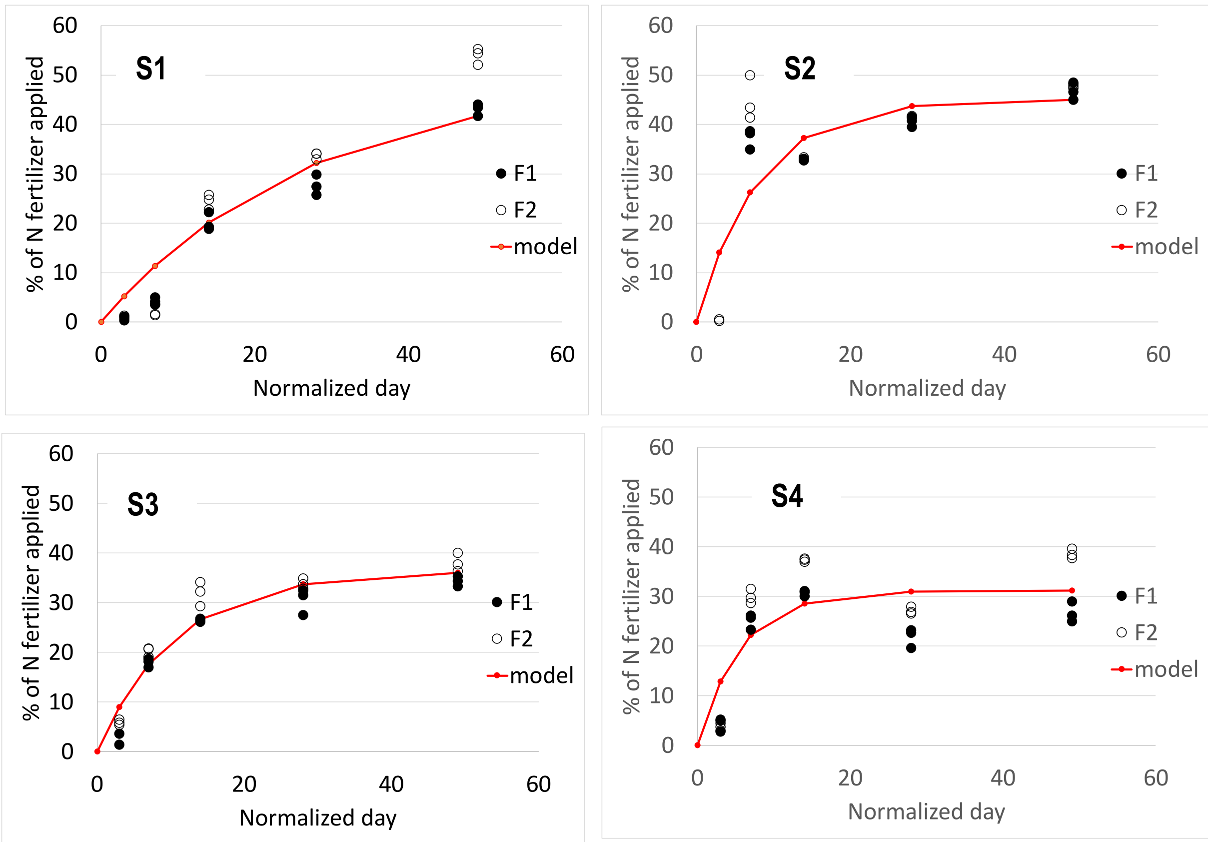

Figure 7: Net nitrogen mineralisation curves as a function of fertiliser type F1 and F2, and first-order kinetics model calibrated on F1 and F2.

Table 5: Model calibration parameters and calibration performance at 20°C and pF2 (Eq. (1)), for each growing medium (n=24), with A the maximum percentage of organic nitrogen mineralised, K the rate of organic nitrogen mineralisation, R^2 the correlation coefficient, and RMSE the root mean square error.

	S1	S2	S3	S4
A (%)	100	45	36	31
K (j^{-1})	0,013	0,125	0,09	0,178
R^2	0,96	0,99	0,97	0,85
RMSE (%)	1	10	4	7

Both models were satisfactory in terms of simulation performance criteria. Nevertheless, both models tended to overestimate the measured values, and the first-order kinetic model overestimated the measured values more (by +12%) in the central range of N contents measured in the growing media (300-1000 mg N kg^{-1}), which concentrates the most data (i.e. 77% of the measured data). Another weakness of these two models is their poorer predictive capacity for either low or high mineralised N levels, which correspond respectively to low (4°C) and high (40°C) temperature conditions that are probably critical for biological activity. Soilless cultivation practices in these extreme temperature conditions remain relatively marginal. Nevertheless, these biases are not *a priori* linked to the temperature action law, which showed good integration of measurements at 4 and 40°C during its calibration (Cannavo et al., 2022). However, the modelling work was carried out without a moisture action law, which was impossible to establish for all the growing media. Even though the modelling work was carried out at a fixed suction (-10 kPa), interactions between temperature and moisture may have occurred, and the model did not take them into account. Further research is needed in this area. Modelling based on first-order kinetics can also be limited by the choice of formalism. We have chosen a model with a single compartment of organic matter, and therefore a single mineralisation rate. Several mathematical formalisms for first-order kinetics exist, taking into account one or more organic matter pools associated with specific mineralisation constants.

2.3 Validation of models on an independent data set at experimental stations

Validation of the models on a dataset other than the laboratory incubations was a major challenge in order to confirm our results. The experimental data acquired during the project, used for the independent validation of the two models developed, covered a wide range of environmental conditions in terms of temperature range (-0.1 to 41.7°C), growing medium diversity and amount of nitrogen supplied by the fertiliser (777-1967 mg N kg^{-1}). For temperature, some values were outside the model's calibration range, but these were very occasional measurements, and we assume that they had little impact on our results. The models gave a good representation of the measured values, which is a very encouraging result. However, there was the same tendency to overestimate the observed values. The multivariate model was closer to the observed values (RMSE=220 mg N kg^{-1}) than the first-order kinetic model (RMSE= 256 mg N kg^{-1}) (Figure 7). This does not mean that agronomic models are not good, as they are widely used in agrosystems and have demonstrated their predictive capabilities. However, these agronomic models have often been established in specific soil and climate contexts, for specific crop species, which limits their ability to extrapolate or generalise results. In our study, these models gave very good results when calibrated for each growing medium.

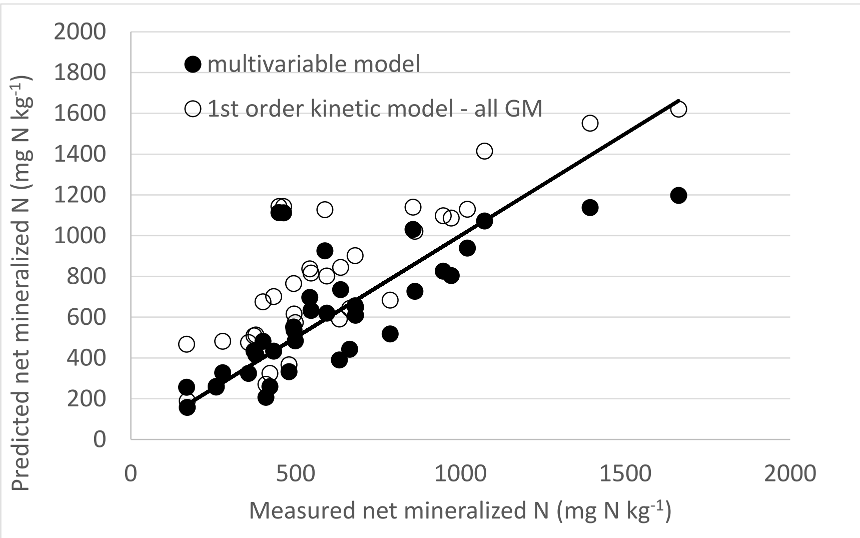

Figure 7: Prediction of net mineralised N content during in situ experiments.

2.4 Research into indicators for on-site management - Development of field tools

The two types of indicators (NO_3^--N content in the growing medium and chlorophyll content) were used on the different systems and decision rules were defined beforehand. The rule consisted in triggering surfacing when the value of the indicator fell by 20 to 30% compared with the values measured on the mineral fertilisation route.

Tests on the various devices show that:

- Monitoring NO_3^--N in the growing medium (Nitracheck®) can reveal a relatively early drop in levels, which is useful for crops where deficiencies only appear late. Monitoring ammoniacal nitrogen is more difficult, as concentrations are often low and ammonia is not detectable. There are, however, measuring strips with a range of 0.2 to 7 mg/L NH_4^+. However, these two indicators linked to measurements of mineral nitrogen in the substrate have proved to be relevant and complementary. The measurement of ammoniacal nitrogen (using the RQ-Flex® box) provides information on whether or not mineralisation is taking place. In hot weather, nitrification proceeds correctly and ammoniacal nitrogen is not detectable because it is too fleeting. On the other hand, in cold weather, ammoniacal nitrogen can accumulate and become a problem for the crop.
- Monitoring the chlorophyll index is more complex when it comes to interpreting the results. Decreases in chlorophyll content are not always linked to a deficiency in mineral nitrogen; they may be linked to deficiencies in other elements (e.g. iron). As a general rule, the decision rule defined upstream (20 to 30% reduction in value compared with mineral fertilisation) is not appropriate. The top dressing was applied too late. This type of indicator is nonetheless interesting for monitoring the physiological state of plants, as it is simple to use and non-destructive. This indicator is linked to the leaf colour index, which reflects the chlorophyll content, the latter being correlated with the state of nitrogen nutrition. The evolution curves obtained with the two N-Tester® and Apogée® devices are comparable, but the results of the Apogée® device are easier to interpret and more detailed. With the Apogée®, the units are expressed in absolute values (chlorophyll concentration in µmol.m^{-2}) whereas with the N-Tester®, they must be transformed into classes to display statistically correct data. In the latter case, reading the results is more complex.

At the end of this first year of study, it appears that each indicator has a very specific interest. The final monitoring tool will probably use several of these indicators depending on:

- Types of crops (short or long cycle),
- The leaves size (chlorophyll tweezers are more difficult to use on plants with small leaves),
- The propensity of the plant species to express a foliar deficiency,
- The growing season (cold or hot).

Conclusion and outlook

The OptiFaz project (i.e. optimisation of organic nitrogen fertilisation) has generated original knowledge and references in the field of organic fertilisation in soil-less production. The growing media studied showed different mineralisation responses depending on the fertiliser used, due to their specific bio-physicochemical properties. Two models for predicting organic nitrogen mineralisation were developed. The multivariate model has a slightly better predictive capacity than the first-order kinetics model, the latter having been adapted to organic growing media. The encouraging results of this project need to be developed further. First of all, the predictive quality and range of validity of the models developed need to be strengthened by studying a larger number of different growing media. In a context of resource independence, growing media without peat or coconut fibre should be taken into account. Mineral growing media such as rockwool are widespread and should be studied. As far as fertilisers are concerned, the range studied should also be extended to include liquid fertilisers, and fertilisers of contrasting types should be selected in terms of mineralisation dynamics on the basis of their stoichiometry, the manufacturing process, the origin of the raw materials, etc.). Finally, the OptiFaz project was conducted in the absence of plants. We now need to integrate the plant and assess the impact of the rhizosphere on the process of organic nitrogen mineralisation and the absorption of mineralised nitrogen by the plant. These research initiatives will need to be validated within the horticultural industry by carrying out in situ cultivation trials.

Ethics

The authors declare that the experiments were carried out in compliance with the applicable national regulations.

Declaration on the availability of data and models

The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.

The authors have used artificial intelligence-assisted technologies to translate from French to English.

Author ORCIDs

Patrice Cannavo: 0000-0002-5689-3843
René Guénon: 0000-0003-2237-8795
Sylvie Recous: 0000-0003-4845-7811

Authors' contributions

Conceptualization, S.B., M.V., P.C., R.G., M.A.J., O.Y. and M.B.; methodology, S.B., M.V., P.C., R.G., M.A.J., O.Y. and M.B.; validation, S.B., M.V., P.C., R.G., M.B., M.A.J., O.Y. and S.R.; formal analysis, P.C., R.G., S.R., M.V., M.A.J., O.Y. and M.B., investigation, P.C., R.G., S.R., M.V., S.B., M.A.J., O.Y. and M.B.; writing—original draft preparation, M.V., P.C., R.G., M.A.J., O.Y. and M.B.; writing—review and editing, P.C.; visualization, P.C., R.G., S.R., M.V., S.B., M.A.J., O.Y. and M.B.; supervision, S.B., M.V., P.C., R.G., M.A.J., O.Y. and M.B.; project administration, S.B.; funding acquisition, S.B., M.V., P.C., R.G., M.A.J., O.Y. and M.B. All authors have read and agreed to the published version of the manuscript

Declaration of interest

The authors declare that they do not work for, advise, own shares in, or receive funds from any organisation that could benefit from this article, and declare no affiliation other than those listed at the beginning of the article.

Declaration of financial support

This project was funded by the CASDAR, Projet OptiFaz, convention number 5746.

References

AFNOR Amendements du Sol et Supports de Culture-Détermination des Propriétés Physiques-Masse Volumique Apparente Sèche, Volume D'air, Volume d'eau, Valeur de Rétraction et Porosité Totale. NF EN 13040. U44-307. 2000a. Available online: https://www.boutique.afnor.org/normes

AFNOR Amendements du Sol et Supports de Culture-Détermination du pH. NF EN 13037. U44-308. 2000b. Available online: https://www.boutique.afnor.org/normes.

AFNOR Amendements du Sol et Supports de Culture-Détermination de la Conductivité Electrique. NF EN 13038. U44-309. 1998. Available online: https://www.boutique.afnor.org/normes

Brisson N., Launay M., Mary B., Beaudoin N, 2008. Conceptual basis, formalisations and parameterization of the STICS crop model. Ed. Quae, 301p.

Burnett S.E., Mattson N.S., Williams K.A, 2016. Substrates and fertilizers for organic container production of herbs, vegetables, and herbaceous ornamental plants grown in greenhouses in the United States. Scientia Hortic 208, 111-119

Caldwell B.A., 2005. Enzyme activities as a component of soil biodiversity: A review. Pedobiologia 49, 637-644

Cannavo P., Recous S., Parnaudeau V., Reau R., 2008. Modeling N dynamics to assess environmental impacts of cropped soils. Advances in Agronomy 97, 131-174

Cannavo P., Recous S., Valé M., Bresch S., Paillat L, Benbrahim M., Guénon R., 2022. Organic Fertilization of Growing Media: Response of N Mineralization to Temperature and Moisture. Horticulturae, doi.org/10.3390/horticulturae8020152

Cannavo P., Recous S., Valé M., Bresch S., Benbrahim M., Guénon R, 2023. Prediction of nitrogen mineralization in organically fertilized growing media for soil-less production. J. Plant Nutr. Soil Sci., DOI: 10.1002/jpln.202300082

Jerkebring K., 2003. Växande marknad - försäljning, volymer och trender för ekologisk mat 2003. Ekologiska Lantbrukarna.

Ma L., Shaffer M. J., 2001. A review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. In "Modeling Carbon and Nitrogen Dynamics for Soil Management." pp. 55-102. Lewis Publishers, Boca Raton, FL, USA

Nicolardot B., Recous S., Mary B., 2001. Simulation of C and N mineralisation during crop residue decomposition: A simple dynamic model based on the C:N ratio of the residues. Plant Soil 228, 83-103

Tittarelli F., Båth B., Ceglie F.G., García M.C., Möller K., Reents H.J., Védie H., Voog, W., 2017. Soil fertility management in organic greenhouse: an analysis of the European context. Acta Hortic [International Society for Horticultural Science (ISHS)], Leuven, Belgium, pp. 113-126