



Status quo of fertilization strategies and nutrient farm gate budgets on stockless organic vegetable farms in Germany

Sophie Stein · Jens Hartung · Sabine Zikeli · Kurt Möller · Hans Jürgen Reents

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Abstract Fertilizer management in stockless organic vegetable production is strongly affected by external nutrient purchases due to the high nitrogen (N) and potassium (K) requirements of vegetables. However, the database on nutrient flows and budgets in organic vegetable farming in Europe is very limited. Therefore, a survey based on semi-structured interviews was carried out comprising 12 organic horticultural farms in Germany. The results show that

three different main fertilizer categories are used as inputs in different ratios by the inventoried farms: (1) base fertilizers (e.g., composts, solid farmyard manures), (2) commercial organic N fertilizers (e.g., keratins or plant products from food production or fermentation processes), and (3) commercial mineral fertilizers (e.g., potassium sulfate), all of which are approved for organic production. Ninety percent of the total nutrient inputs to the farms came from these fertilizers and biological N₂ fixation, with the remaining 10% coming from other inputs, such as seeds or growing media. The estimated yearly average total farm budgets were nearly balanced across all farms with moderate surpluses (67.5 kg N ha⁻¹, 2.06 kg P ha⁻¹, and 0.26 kg K ha⁻¹). However, large imbalances were found for most of the individual farms. These imbalances indicate the risk of nutrient accumulation or nutrient depletion in the soil, depending on the fertilization strategy and productivity of the farm. More specifically, increasing N share from base fertilizers led to increased P and K budgets, while strategies based on the use of large amounts of keratins led to the opposite—K and P depletion. We concluded that balanced nutrient management in organic vegetable production systems requires a thorough calculation and should combine the use of base fertilizers, commercial fertilizers with low P content, and increased N supply via BNF.

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S. Stein (✉) · S. Zikeli
Center for Organic Farming, University of Hohenheim,
70599 Stuttgart, Germany
e-mail: sophie.stein@uni-hohenheim.de

J. Hartung
Department of Biostatistics, Institute for Crop Science,
University of Hohenheim, 70599 Stuttgart, Germany

K. Möller
Department of Fertilization and Soil Matter Dynamics,
Institute of Crop Science, University of Hohenheim,
70599 Stuttgart, Germany

K. Möller
Center for Agricultural Technology Augustenberg, Institute
of Applied Crop Science, 76287 Rheinstetten, Forchheim,
Germany

H. J. Reents
Chair of Organic Agriculture and Agronomy, Technical
University of Munich, 85354 Freising, Germany

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Introduction

The principles of organic farming have a strong focus on soil fertility and include the “Law of Return” (Howard 2011), which refers to the internal cycling of nutrients via base fertilizers like farmyard manure or compost as a major pillar of soil fertility management. Furthermore, nutrients should be supplied to the soil by using legumes for biological N₂ fixation (BNF) in addition to the maintenance and improvement of soil organic matter through appropriate tillage and cultivation practices (IFOAM 2019). Only if these management measures are not sufficient for the nutrient supply of crops, additional approved fertilizers can be used to replenish nutrients lost via sold products ((EU) 2018/848 2022). This is particularly relevant for organic horticultural production as most of the vegetable crops have a high nutrient demand within a comparatively short growing period. For most vegetable crops, e.g., the *Brassicacea* species cauliflower, broccoli, or cabbage, nitrogen (N) and potassium (K) requirements are high while the requirement for phosphorus (P) is similar or relatively low in comparison to arable crops like cereals (Feller et al. 2011; Möller 2018). As horticultural farms are often highly specialized and therefore have little or no animal husbandry, on-farm feed and fertilizer production, e.g., grass-clover leys and farm-produced animal manures, play a minor role in their cropping systems. Therefore, off-farm nutrient sources play a considerably higher role than in mixed farm systems.

Stockless organic vegetable farms may import different types of fertilizers. By purchasing manures and composts within the scope of a fodder-manure cooperation, the nutrient supply on stockless vegetable farms can still be achieved via base fertilizers. Base fertilizers generally have low N contents, are strongly P-balanced, and have a slow nutrient availability (Eghball 2002; Möller 2018; Möller and Schultheiß 2014). Long-term application thus may lead to over-fertilization and build-up of P stocks in the soil, especially in protected vegetable cultivation (Cooper et al. 2018). It is generally difficult to find a suitable nutrient stoichiometry of base fertilizers for use in organic horticulture, which explains the frequently observed P surpluses (Möller 2018; Tittarelli

et al. 2017; von Fragstein und Niemsdorff et al. 2004; Voogt 2014; Zikeli et al. 2017). Due to their origin and their source material, fertilizers such as biogas digestates and champost can also be included in the category of base fertilizers with similar characteristics (DüV 2017), although they are generally still seldom used. Alternatives to the base fertilizers are the organic commercial fertilizers, which can be either animal-based or plant-based. Horticultural farms using animal-based commercial fertilizers, which as keratins are rich in N and available fast, can show N use efficiencies (NUE) approaching those of conventional systems (Zikeli et al. 2017). Due to the almost complete absence of other nutrients, keratins are N fertilizers without any mentionable ratio to P and K. Those keratin fertilizers, namely horn and hoof shavings, feather meal, and pig bristles, are based on residues from intensive conventional livestock production or are often imported from developing countries. This results in a systemic contradiction to the overall principles of organic farming (Möller and Schultheiß 2014; Zikeli et al. 2017). In contrast to keratin fertilizers, plant-based commercial fertilizers still have certain proportions of other nutrients in addition to N and can therefore be classified together with base fertilizers as multi-nutrient fertilizers. Another important group of fertilizers in organic horticulture are mineral K fertilizers for the sufficient supply of the vegetable crops in high demand. Similar to keratin fertilizers for N, mineral K fertilizers can be used to replenish deficient K fertilization with base fertilizers.

Current fertilization practices in horticulture suggest that aligning the amount of fertilizer with the N requirement leads to a surplus or to deficiencies of P and K depending on the shares of fertilizer types. Farm gate budgeting is an easy-to-use tool for investigating the input–output nutrient fluxes and N use efficiency (NUE) on a farm. Previous studies using farm gate budgets to investigate nutrient levels indicate imbalances in N, P, and/or K in organic vegetable production (Cuijpers et al. 2008; Reimer et al. 2020b; Tittarelli et al. 2017; Watson et al. 2002; Zikeli et al. 2017). However, the number of investigated farms was small or the studies focused on a particular farm type, e.g., organic vegetable greenhouse production (Cuijpers et al. 2008; Tittarelli et al. 2017; Zikeli et al.

2017). It is therefore difficult to derive general explanations for these frequently occurring imbalances in organic vegetable farms.

In the present study, nutrient budgets for N, P, and K were analyzed for organic stockless vegetable farms in South-West and Western Germany. The aim of our study was to create and expand a database and to get a better understanding of the fertilization strategies in organic horticulture. Our research questions were the following:

1. Is there a relationship between the nutrient input and output measured as overall productivity?
2. Which are the main fertilizers used in organic vegetable production and what are their nutrient ratios?
3. Does the fertilization strategy influence the nutrient budget for N, P, and K on organic vegetable farms and what might be the reasons for the occurrence of nutrient imbalances?
4. What is the relationship between the fertilizer categories of base fertilizers and keratins with their respective N:P ratios?

Based on these results, this study aims to formulate recommendations for nutrient and fertilization management on organic horticultural farms.

Table 1 Overview of participating farms in the different German federal states, year of conversion (YOC), membership in organic growers' association, average usable agricultural area

Farm	State	YOC	Association/certification	Avg. area (ha)	Avg. no. of crops	YDC
1	BW	1988	Demeter	13	5.0	3
2	BW	1990	Demeter	39	45.3	3
3	BW	1984	Demeter	5	48.7	3
4	RLP	2009	EU	59	8.3	3
5	NRW	1980	Bioland	30	30.0	1
6	NRW	1995	Bioland/Naturland	239	13.5	2
7	NRW	1993	Demeter	9	34.5	2
8	BY	1996	Naturland	2	29.7	3
9	BY	1986	Demeter	108	9.0	1
10	BY	1986	Bioland	60	11.7	3
11	BY	1986	Naturland	58	28.5	2
12	BY	1994	Biokreis	363	13.0	1

BW Baden-Württemberg, *RP* Rhineland-Palatinate, *NRW* North Rhine-Westphalia, *BY* Bavaria, *EU* Certification according to EU regulation on organic production and labelling ((EU) 2018/848 2022), *Demeter/Naturland/Bioland/Biokreis* German organic growers' associations

Material and methods

Description of farm sample

Twelve organic vegetable farms participated in the survey on farm gate budgets. Criteria for farm inclusion were (i) the organic cultivation of vegetables, either intensively as a specialized horticulture farm or extensively as a vegetable-arable mixed farming system and (ii) no or minor animal husbandry (<0.2 livestock units ha⁻¹; only Farm 2 had chicken husbandry). Farms were located in the German federal states of North Rhine-Westphalia, Rhineland-Palatinate, Baden-Württemberg, and Bavaria. The survey aimed to collect data for 3 years (between 2017 and 2020) per farm, but in some cases, only 1 or 2 years could be collected due to data availability or farmers' time constraints. Data from conventional fields as well as greenhouses and plastic tunnels were not included in the budget analysis for this study. The farms differed in year of conversion, farm size, number of cultivated crops, and memberships of organic growers' associations (Table 1).

Data collection

The farmers were interviewed in 2021 about their nutrient management in order to carry out an

in hectare (ha), average number of crops, and number of years covered for data collection (YDC)

inventory of all flows relevant for calculations of farm gate budgets for the three main nutrients N, P, and K. For total nutrient inputs, the amount of imported nutrients via fertilizers, growing media, seeds, animals, and feed were inventoried, and the amount of BNF from legume cultivation was assessed. For total nutrient output, the amount of exported nutrients via plant products, fertilizers, feed, and animal products was compiled. The “Nutri gadget-Hohenheim Organic Nutrient Budget Calculator” developed by Reimer et al. (2020a) for organic arable farms, extended by the project “DüngungsNetzwerk BW” led by the Center for Agricultural Technology Augustenberg (Karlsruhe, Germany) and adapted to this research project was used for calculations of the quantities recorded on the farms with the corresponding nutrient contents. The initial tool and the adapted version for farm gate nutrient budgets on organic vegetable farms are available online (<https://orprints.org/38025/> and <https://orprints.org/id/eprint/44772/>). The nutrient contents of organic commercial fertilizers were determined according to Möller and Schultheiß (2014) and adjusted if specific manufacturer or product data were available. If available, data from analyses for farm-specific base fertilizers were used. The data sets for the calculations are primarily taken from the master data sets of “Düngung BW” (<https://www.duengung-bw.de/landwirtschaft/views/informationen.xhtml>) published by Agricultural Technology Center Augustenberg. The additional data sets were taken from tables of the German Fertilizer Ordinance (DüV 2017) and the fertilization planning and nutrient balancing tool N-Expert from the Leibniz Institute of Vegetable and Ornamental Crops (<https://n-expert.igzev.de/downloads/>, Feller et al. 2011). Standard organic yields were compiled from a comparison of federal statistical surveys (https://www.destatis.de/DE/Home/_inhalt.html) and were used when data on yields were missing. The calculation of BNF by legumes in the tool is based on algorithms from REPRO, a tool for sustainability analysis of agricultural farms (Hülsbergen 2003).

Depending on the crop, the harvest quantities on the farms were not always documented as mass, but in packaging units such as boxes, pieces, and bundles. Based on literature data and own weighing (<https://www.lebensmittelwissen.de/tipps/haushalt/portionsgroessen/gemuese.php>, Seifert 2020), a documentation of

the conversion from packaging unit to weight was created, included as a spreadsheet in the tool and used for the evaluation. An additional nutrient input in vegetable cultivation occurs via the purchase of seedlings and thus the growing media for seedlings’ press pots. Unlike the seedling, which leaves the farm at the end of vegetation period as the harvested product, the growing media remains in the soil on the farm. For the nutrient contents and the conversion of quantities from volume to mass, a table for the growing media was prepared and included as spreadsheet in the tool. Data were obtained from the main growing media manufacturer in Germany.

Data processing and statistical analysis

Ordinary means per farm for the variables of fertilizer N input, nutrient ratios of fertilizer input, as well as plant product output, and N, P, and K budgets were calculated as descriptive statistics. The relationship between N supply via base fertilizers and the P or K farm gate budget as well as between the N supply via base fertilizers or via keratin fertilizers with BNF and the N:P ratio of the fertilizer input was presented in scatter plots (Figs. 5 and 6).

The yearly budgets for the nutrients N, P, and K for the i -th farm were calculated with Eq. (1):

$$\text{Nutrient budget}_{ij} [\text{kg ha}^{-1} \text{a}^{-1}] = \text{Nutrient input}_{ij} - \text{Nutrient output}_{ij} \quad (1)$$

where i is the index of the farm i and j is the index of year j . The yearly nutrient input for each macronutrient was calculated for each farm based on Eq. (2):

$$\begin{aligned} \text{Nutrient input}_{ij} [\text{kg ha}^{-1} \text{a}^{-1}] = & \text{BNF}_{ij} \\ & + \text{NCFert}_{ij} + \text{NCS}_{ij} + \text{NCPS}_{ij} + \text{NCFS}_{ij} \\ & + \text{NCA}_{ij} + \text{NCFeed}_{ij} \end{aligned} \quad (2)$$

where BNF_{ij} is the N input via biological N_2 fixation at the i -th farm in the j -th year. The amount of N supplied via BNF is included in all calculations of the fertilizer input as long as it is not explicitly described as excluded. NCFert_{ij} is the nutrient content of fertilizers used in farm i in year j . NCS_{ij} , NCPS_{ij} , NCFS_{ij} , NCA_{ij} , and NCFeed_{ij} are the nutrient contents of the seeds, press pot growing media, feedstock, animals, and feeds used in farm i in year j , respectively. The term “base fertilizers” in the results and discussion

describes the sum of the input via farmyard manures, composts, champost, and biogas digestates.

The total yearly nutrient output at farm i for each macronutrient was calculated for each farm with Eq. (3):

$$\text{Nutrient output}_{ij} [\text{kgha}^{-1}\text{a}^{-1}] = \text{NCPP}_{ij} + \text{NCAP}_{ij} + \text{NCFS}_{ij} + \text{NCFeed}_{ij} \quad (3)$$

where NCPP_{ij} i and NCAP_{ij} are the nutrient content of the harvested plant products and animal products, respectively. All other variables were analogously defined compared to Eq. 2.

To assess the performance of agricultural production on the farms, the indicators' nutrient productivity, defined as nutrient output per unit nutrient input, and N use efficiency (NUE), defined as unit nutrient output per nutrient input, were calculated as the slope from the regression of N output on N input of the farm gate system (Oenema et al. 2015; Congreves et al. 2021).

Since the literature mainly refers to the term N:P ratio, estimated means per farm and year were used to calculate ratios between the nutrients after analysis with P or K in the denominator and N in the numerator. The calculated values of the N:P and N:K ratios were used in order to be comparable to the literature and other studies. However, for illustration, the inverse of the ratios (the P:N and K:N ratios) was shown in Figs. 3 and 4.

Mean values for the traits across farms were calculated using a one factorial analysis of variance. The model can be described as (4):

$$y_{ij} = \mu + f_i + e_{ij} \quad (4)$$

where y_{ij} is the observation of the farm i at year j , μ is the intercept, f_i is the random effect of the i -th farm, and e_{ij} is the error from y_{ij} . The model was extended by adding linear relations between predictive variables (e.g., N input, base fertilizers) and response variables (e.g., N output). The slope of output on input was denoted as nitrogen use efficiency (NUE). In this case, the model was further allowed to have farm-specific slopes. As farms were assumed to be random, an unstructured variance–covariance matrix between farm effect and its random slope effect was fitted. The coefficient of determination in regression models was calculated using the %omega macro (Piepho 2023). In case the estimate of the coefficient of determination was negative, it was set to zero. All calculations and

analyses were performed with the statistical program SAS (Statistical Analysis Systems ver. 9.4, SAS Institute, Cary, NC) and displayed with Microsoft Excel.

Results

Nutrient inputs of fertilizers and fertilizer ratios

To identify the sources of nutrient inputs within the farm gate budgets, 13 different general input types were defined (Fig. 1). On average, fertilizers comprise the largest proportion of inputs for N, P, and K at 90% or even more, while other inputs like growing media and feeds provided less than 10% of the overall inputs. For N, BNF at 29% and keratin fertilizers at 26% provided the highest proportion of total N inputs. Approximately 16% of the total N input was provided by manures; together with composts (9%), champost (2%), and biogas digestates (4%), the category of base fertilizers provided 31% of the N inputs, and 62% of the total P inputs (Supplementary Tab. 1). For K, manures had the highest input proportion at 33%, followed by mineral fertilizers at 21%.

Compared to the number of sources for total nutrient input, the number of different fertilizer N sources on each farm was less diverse shown by the proportion of fertilizer N input (Fig. 2). For instance, Farm 8 used only one external N fertilizer—keratin fertilizers—and BNF as N inputs, while Farm 12 had up to five different N fertilizer sources. The proportion of N provided by BNF ranged from 7 (Farm 8) up to 56% (Farm 1). Except for Farms 6, 7, 10, and 11, all farms used keratin fertilizers. Farms 3 and 7 showed the highest proportion of N inputs provided by manures at 62% and 41%, respectively. Plant-based commercial organic fertilizers were used on seven and composts were used on four of the farms. Only Farm 6 used champost, which accounted for 20% of its total fertilizer N input. Farms 11 and 12 used biogas digestates at proportions of 1% and 42% of the total fertilizer N inputs. Potassium sulfates as mineral K fertilizers were used on half of the farms (Farms 1, 2, 5, 6, 10, and 11) in shares of 14% at Farm 1 and 66% at Farm 5.

When comparing the N:P ratios of vegetable and arable crops cultivated on the 12 farms, they differed only slightly (5.75 and 5.26, respectively);

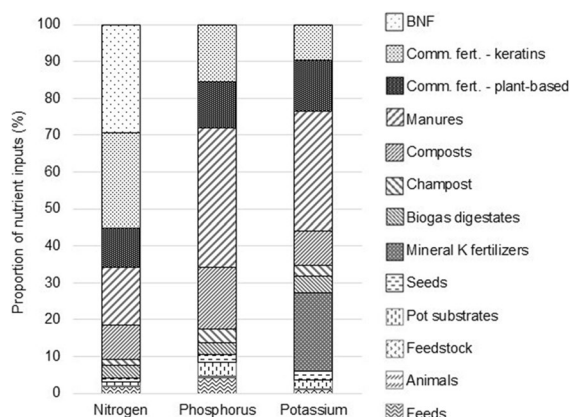


Fig. 1 Proportion of nutrient inputs by source in total nutrient input, averaged across all years of data collection and all 12 farms. Abbreviations: BNF, biological N_2 fixation, Comm. fert., commercial fertilizers

however, there were only a few arable crops cultivated on the investigated farms, mainly cereals, but also some potatoes, corn, sugar beet, and legume forages. In contrast to the N:P ratio, the N:K ratio differed between vegetables (0.70) and arable (1.77) crops. The nutrient stoichiometry among the different fertilizer inputs used on the farms varied (Fig. 3). Keratins mainly consist of N- and S-rich proteins, and therefore, their P and K content is very low, resulting in a very high N:P ratio of 43.4. Solid base fertilizers like champost and solid farmyard manures showed

the lowest N:P ratio with 2.41 and 3.30, respectively. The lowest N:K ratios, which would be preferable for vegetable crops, were found in manures and biogas digestates with 0.81 and 0.82, respectively. In addition to keratin fertilizers with an N:K ratio of 73.3, the plant-based composts had a high N:K ratio of 1.48.

On the individual farms of the survey, the stoichiometry of the total fertilizer inputs also varied more for the N:K ratio than for the N:P ratio (Fig. 4a). Inputs of Farms 1, 4, 5, 8, and 9 had markedly higher N:K ratios than the average offtakes of the vegetable crops across the 12 farms. In comparison, the inputs of Farm 10 had a very low N:K ratio. Farm 6 showed the lowest N:P ratio of the fertilizer inputs. Farm 11 and Farm 12, in particular, showed a stoichiometry which fits very well with that of the average vegetable crops offtake. While Farm 11 has a high K input via mineral K fertilizer of 63 kg ha^{-1} , the high K input in Farm 12 derives from digestates and potato syrup as plant-based commercial fertilizer. In contrast to the fertilizer inputs, the stoichiometry of N, P, and K in the outputs via plant products of each farm differed much less than the stoichiometry of the fertilizer inputs (Fig. 4b), even though the number of crops cultivated at the different farms varied from 5 and up to 50 (Table 1) and included different vegetable families and types, e.g., root vegetables, salads, brassica species, and many others.

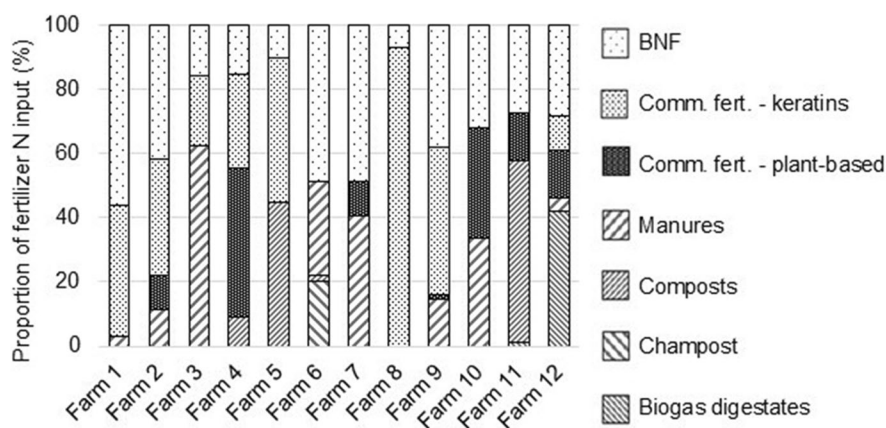


Fig. 2 Proportion of fertilizer nitrogen (N) input of total fertilizer N input, averaged across all years of data collection. Abbreviations: BNF, biological N_2 fixation, Comm. fert., commercial fertilizers

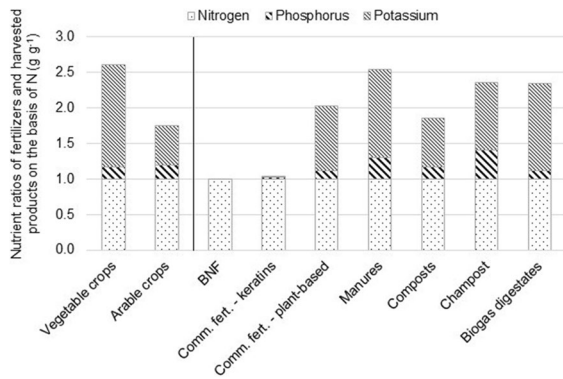


Fig. 3 Nutrient stoichiometry: ratios of phosphorus and potassium in g g^{-1} based on N content in different fertilizer inputs compared to the ratios of vegetables and arable crops, averaged across the 12 farms and years of data collection. Abbreviations: BNF, biological N_2 fixation, Comm. fert., commercial fertilizers

Nutrient productivity on organic horticultural farms

In order to determine the nutrient productivity on the farms, the regression between the total nutrient in- and outputs was calculated, and the slope was interpreted as NUE. There was a positive relationship between the N input and the respective N output in kg ha^{-1} with a coefficient of determination of $R^2=0.15$ (Table 2). A stronger relationship between the N input of a fertilizer group and the N output was shown for biogas digestates with a coefficient of determination of $R^2=0.34$. However, only two farms applied digestates. For the eight farms using keratin fertilizers, the relation between N input and N output was $R^2=0.26$. Further regressions and their coefficient of determination of N input from different fertilizer groups and the N output are shown in Table 2.

For P and K, the relationship between their input and output resulted in estimated R^2 values of 0.03 and 0, respectively (data not shown). A stronger positive relationship, however, could be shown between the N input and K output in kg ha^{-1} with $R^2=0.41$ ($p=0.0027$ for the test of the slope against zero) (data not shown). The relationship of N input to P output had a coefficient of determination of $R^2=0.15$ ($p=0.0263$, for the test of the slope against zero) (data not shown).

The NUE as quotient of output and input had an average value of 0.53 (=53%) across the 12 farms. Farm 12 had the highest NUE of 1.10 (Table 3). The

relationship between P or K input in kg ha^{-1} and NUE had coefficients of determination of $R^2=0$, respectively (P, $p=0.3772$; K, $p=0.7456$) (data not shown).

Farm gate nutrient budgets

The averaged farm gate nutrient budgets showed a surplus of $67.5 \text{ kg N ha}^{-1}$, $2.06 \text{ kg P ha}^{-1}$, and $0.26 \text{ kg K ha}^{-1}$ (Table 4). The range among the farms was particularly wide for N (-13.4 to $+176.8 \text{ kg ha}^{-1}$) and K (-86.7 to $+60.6 \text{ kg ha}^{-1}$). Farm 5 and Farm 9 showed the highest N surplus of more than 120 kg ha^{-1} . The highest P surplus was found for Farm 6 with 14.0 kg ha^{-1} , while the highest deficiency was calculated for Farm 8. The K budgets were particularly high for Farm 10 (60.6 kg ha^{-1}) and low for Farm 8 (-86.7 kg ha^{-1}).

Nutrient budget and N:P ratio in relation to fertilizer input

Depending on the proportion of N supplied via base fertilizers, the farm gate budgets increased with coefficients of determination of $R^2=0.48$ for P (Fig. 5a) and $R^2=0.19$ for K (Fig. 5b). Farms supplying more than 40% of their fertilizer N inputs via solid base fertilizers were more likely to show P surpluses $> 5 \text{ kg P ha}^{-1}$ (Fig. 5a). Again, Farm 12 stood out with a high proportion of liquid digestates as bulky base fertilizer N source and a simultaneous P deficiency in its farm gate budget. Farm 8 had the strongest P deficiency in the budget and did not supply any N via base fertilizers. In contrast to P, for K, two distinct groups became apparent, showing a relationship between the N supply via base fertilizers and the farm gate budget (Fig. 5b). Farms with an N supply via base fertilizers below 20% showed deficiencies whereas most farms with a supply above 40% showed surpluses, with the exception, again, of Farm 12 which had a high share of liquid digestates as fertilizer source.

The proportion of N supply via fertilizer categories (light grey circles, nearly P- and K-free keratin fertilizers in combination with N-exclusive BNF; dark grey squares, base fertilizers) showed a relationship to the overall N:P ratio of the fertilizer input of $R^2=0.70$ for keratin fertilizers in combination with BNF and $R^2=0.71$ for base fertilizers

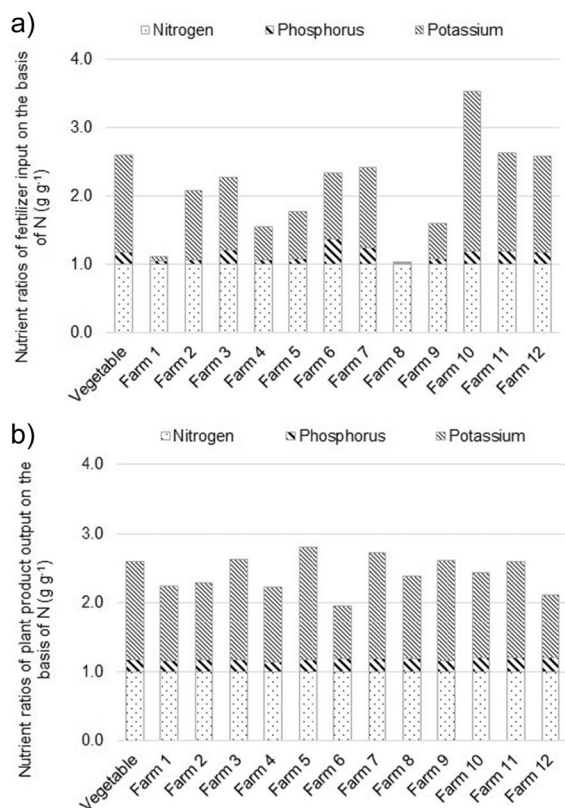


Fig. 4 Nutrient ratios of **a** total fertilizer inputs and **b** plant product outputs of each farm compared to the average nutrient ratio of the vegetable crops across the 12 farms on the basis of nitrogen (N) in g g^{-1} , averaged across the years of data collection

(Fig. 6). The N:P ratio calculated across all farms from the reference output by vegetable crops was 5.75. Farms with a fertilizer input ratio close to the vegetable output ratio had similar ratios of the proportions of N supply via keratin fertilizers with BNF and via base fertilizers. The N:P ratio, in

contrast, did not show a relationship to the farm gate budgets with a coefficient of determination of $R^2 = 0$ for N, P, and K (data not shown).

Discussion

Fertilizer strategies on organic vegetable farms and their influence on overall productivity

Vegetable crops are well-known as crops with a moderate to very high N demand (Cuijpers et al. 2008; Zikeli et al. 2017), which—on stockless farms—have to be supplied via BNF and via external fertilizers. However, considering the first research question of this study, in the present inventory, a relationship between the external total N input and the N output at the farm gate level of $R^2 = 0.15$ was found. Therefore, a high input of external N does not automatically lead to a high N output (productivity) as expected. Not only was there low overall productivity but there was also a low NUE. This result differs markedly from that of Reimer et al. (2020a), whose survey on arable organic cropping systems found higher productivity with increasing external fertilizer N inputs at the same nutrient input levels as in the present study. The driving factors for this are not well understood. One explanation could be the mean NUE of approximately 53% (Table 3) in combination with the import of a high share of fertilizers with a slow N release pattern (e.g., solid animal manures and compost). This may overcompensate for the effect of the total external N inputs. The high NUE of 110% (Table 3) and the low budget surpluses (Table 4) of Farm 12 using a high share of fast N-releasing biogas digestates (Fig. 2) support this assumption. Further

Table 2 Relationship between nitrogen (N) input of different fertilizer groups and the N output, averaged across the years of data collection on 12 farms in South and West Germany

Fertilizer N input	Evaluation criteria for N output		
	R^2	Slope parameter	p value ¹⁾
Base fertilizers (without digestates)	0.00	−0.13	0.4764
Biogas digestates	0.34	1.60	0.0025
Total base fertilizers	0.00	0.00	0.9979
Commercial fertilizers—keratins	0.26	−0.57	0.0032
Commercial fertilizers—plant-based	0.13	0.44	0.0004
Total N input via fertilizers + BNF	0.16	0.25	0.0231
Total N input via fertilizers without BNF	0.12	0.24	0.0656
Total N input	0.15	0.25	0.0214

¹⁾ p value as test of slope parameter against zero
BNF biological N_2 fixation

Table 3 Estimated nitrogen use efficiency (NUE) calculated as ratio of total nitrogen input by total nitrogen output on 12 farms in South and West Germany, averaged across the years of data collection

Farm	NUE
Farm 1	0.20
Farm 2	0.88
Farm 3	0.48
Farm 4	0.52
Farm 5	0.29
Farm 6	0.41
Farm 7	0.42
Farm 8	0.47
Farm 9	0.39
Farm 10	0.61
Farm 11	0.59
Farm 12	1.10
Mean	0.53

Table 4 Farm gate nutrient budgets for nitrogen (N), phosphorus (P), and potassium (K) in kg ha⁻¹ on 12 farms in South and West Germany, averaged across the years of data collection

Farm	N budget kg ha ⁻¹	P budget kg ha ⁻¹	K budget kg ha ⁻¹
Farm 1	63.1	-0.22	-13.4
Farm 2	6.03	-2.30	-16.5
Farm 3	48.3	10.3	24.2
Farm 4	77.3	-2.60	-25.1
Farm 5	177	7.08	36.5
Farm 6	74.8	14.0	14.3
Farm 7	83.6	8.71	15.2
Farm 8	83.9	-10.5	-86.7
Farm 9	126	-0.11	-49.5
Farm 10	32.4	0.98	60.6
Farm 11	57.1	6.00	46.4
Farm 12	-13.4	-6.70	-1.26
Adjusted mean	67.5	2.06	0.26

explanations might be high shares of crop residues high in N and non-marketable plants remaining in the field, which are found more often in vegetable than in arable systems. High levels of N in crop residues reduce N fertilizer offtakes in the crops and leave large amounts of N at risk of being lost through nitrate leaching, ammonia volatilization, and/or denitrification (Chaves et al. 2007; De Neve et al. 2003;

De Neve and Hofman 1996; Nett et al. 2016; Ruijter et al. 2010). As a result, the overall NUE assessed at the farm gate level can be reduced. Differences in the N release pattern of different fertilizers (Benke et al. 2017), combined with the effect of a high level of N in crop residues and high amounts of non-marketable waste products (Congreves and Van Eerd 2015), may interfere with each other and overlay the effect of the total amount of N supplied by fertilizer. In summary, the high external nutrient inputs for fertilizing vegetables do not translate into higher N productivity. In order to achieve high N fertilization efficiencies, more fast N-releasing fertilizers, such as liquid digestates or keratin fertilizers, should be included into the fertilization strategy. Enhancement of the NUE can possibly be achieved by purchasing digestates instead of solid animal manures as nutrient sources (Möller and Müller 2012). Another complementary option is to collect the crop residues, digest them via anaerobic digestion, and use the digestates as a fertilizer source in the following season, as previously proposed by Stinner et al. (2008) for organic arable systems, which may also reduce the risk of N emissions and losses (Möller and Stinner 2009). However, the potential reasons for the overall low NUE and for the differences in the effects of external N inputs on the overall productivity in organic arable compared to vegetable farming should be given greater consideration in experimental research.

One aim of this study was to gain insight into fertilizer strategies on organic vegetable farms and to expand the database of nutrient inputs and outputs. For the present study, data from a survey of 12 horticultural farms were used. This number of farms appears small at first. Due to the often unavailable or difficult-to-obtain data (yield data are difficult to estimate due to numerous marketing channels, imprecise information on crop residues and harvest rates, etc.), data collection on organic vegetable farms is challenging. This study is cross-sectional and therefore, in principle, no statements about causalities are possible. For this purpose, subsequent experiments would be necessary. The study might not be representative for the entire sector; however, it comprises the entire range of known fertilizer strategies used in the sector. The survey shows how the farms are managed individually and how their fertilization strategies influence performance regarding nutrient flows and budgets. Present data indicate that there are many patterns

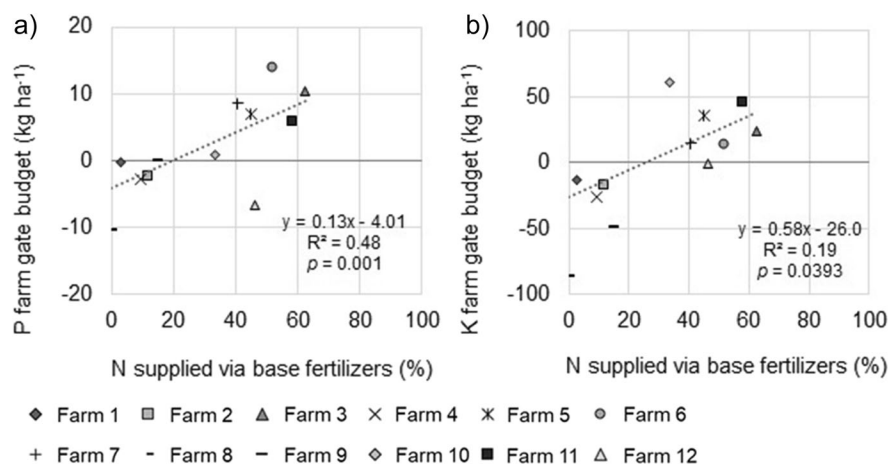


Fig. 5 Relationship between **a** the phosphorus (P) or **b** the potassium (K) farm gate budget in kg ha^{-1} and the amount of nitrogen (N) supplied via base fertilizers in percentage. Each

dot represents the farm average value over all years of data collection. The dotted lines show the linear regression

of soil fertility management. For example, regarding research question no. 2 about the type of fertilizer, the data of the present inventory indicate that vegetable farmers use very different fertilizer products (Fig. 1). Also, there is a wide variety of strategies for combining different fertilizers among the inventoried vegetable organic farms (Fig. 2). Some farms cover their N

input with large amounts of N-rich keratin fertilizers and BNF only (Farm 1, Farm 8); some farms implement strategies mainly based on BNF and the use of solid base fertilizers (Farm 10 and Farm 11). Other farms are more diverse in terms of nutrient sources and use up to five different N fertilizer inputs including relatively rare sources such as biogas digestates

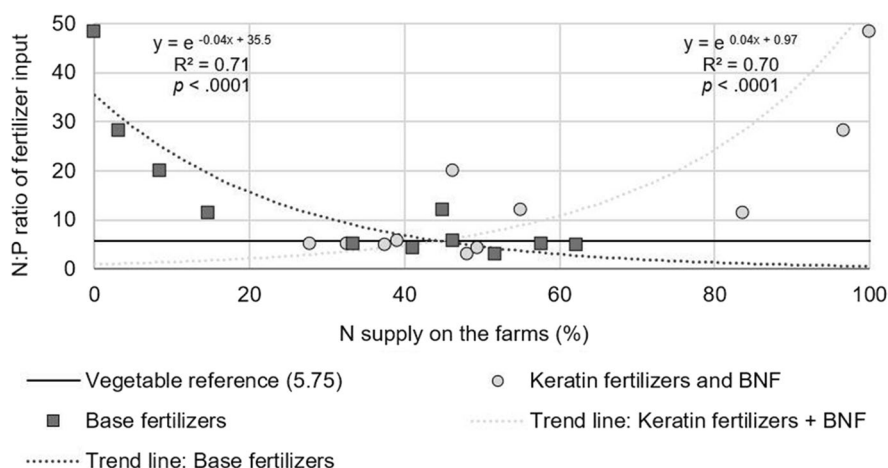


Fig. 6 Exponential regression analysis for the amount of nitrogen (N) supplied via keratin fertilizers and BNF (light grey circles) and base fertilizers (dark grey squares) in the percentage of total fertilizer N input depending on the N:P ratio of farm

fertilizer input. Dark grey line represents the N:P ratio of the vegetable crops output. Each dot, square, and the dark grey line represents the average value per farm across years of data collection. The dotted lines show the exponential regression

(Farm 12). The nutrient ratios of N, P, and K for individual fertilizer types (Fig. 3) and the combination of these on the individual farms (Fig. 4a) vary widely. In contrast, the N:P:K ratio of the farm outputs differ less (Fig. 4b), regardless of how diverse the crop rotation is (Table 1). It can be assumed that nutrient imbalances are caused by one-dimensional fertilization strategies based on mainly supply of enough N for optimal plant growth. However, for efficient, balanced fertilizer strategies, fertilizer inputs with different N:P:K ratios should match the N:P:K ratios of the harvest output. This requires a thorough calculation of N demand in a single year, and the P:K inputs and outputs over a crop rotation, taking into consideration the N:P:K stoichiometry of the fertilizer inputs plus BNF and the stoichiometry of outputs. It can be assumed that most of the farmers interviewed in the present inventory do not consider this aspect of soil fertility management, which indicates deficits in knowledge transfer. Furthermore, thorough calculation of nutrient inventories in vegetable farms is very challenging, as yield data are difficult to estimate due to marketing units (in many cases, the product mass is not considered), harvesting over a longer period of time, numerous marketing channels, imprecise information on crop residues and harvest rates, etc.

Farm gate nutrient budgets in organic vegetable production

Regarding research question no. 3, the fertilization strategy may have considerable effects on nutrient flows and the farm gate nutrient budgets: the data analysis of the individual farms indicates that none of the inventoried farms shows balanced nutrient budgets across all three nutrients N, P, and K (Table 4). Moderate N surpluses are relatively common as N is generally the basis of the fertilization strategy and additionally has several loss pathways after field application that can only be controlled to a certain extent (Congreves and Van Eerd 2015). An N surplus of up to 50 kg ha⁻¹ might still be considered within an acceptable range (Oenema et al. 2015; Reimer et al. 2020b). However, six farms (Farms 4 to 9) had N surpluses above 75 kg N ha⁻¹ far beyond an acceptable range (Oenema et al. 2015). Similarly, most of the inventoried farms showed either considerable surpluses or deficits in P and K. A comparison of these

results with those of other studies in order to interpret the results is rather difficult, since there are only few systematic studies of farm gate budgets in organic field vegetable production (Reimer et al. 2020b).

The positive relationships between the proportion of N supplied via base fertilizers and the P and K farm gate budgets (Fig. 5a, b) may be statistical artifacts, since base fertilizers are compound fertilizers, which—compared to keratin fertilizers or single-nutrient fertilizers—also supply a certain amount of P and K in addition to N. All farms with a supply of N via base fertilizers like compost, solid farmyard manure, or champost above 40% show positive P farm gate budgets (Fig. 5a). This indicates that the overall fertilization strategy should be adapted in a way that reduces the supply of external P-containing fertilizers. The only exception is Farm 12, which applies more than 40% of its fertilizer N input via biogas digestates (Fig. 2), which has the highest N:P ratio of the base fertilizers in the present study and is therefore well suited for vegetable production (Fig. 3) (Maltais-Landry et al. 2016; Möller 2018). In contrast, farms which use a high proportion of nearly P-free keratin fertilizers and BNF for fertilization (e.g., Farm 8 in Fig. 2) showed negative P and K farm gate budgets (Fig. 5a). For the long-term sustainability of a farming system, almost balanced nutrient flows should be aimed for. Even comparatively small P imbalances may result in strong imbalances in the soil in the long term. A P budget of -10.5 kg ha⁻¹ (Farm 8) would reduce extractable P levels by 10 mg kg⁻¹ soil after approximately 10 years, while budgets of 14.0 kg ha⁻¹ (Farm 6) would increase the extractable P levels by 10 mg kg⁻¹ soil after 6–8 years (Knauer 1968; Römer 2009).

The large imbalances in the K farm gate budgets also seem to be related to the proportion of N supplied via base fertilizers: the results from farms with less than 20% N supply via base fertilizers indicate K deficiencies, while above 40% the budgets show surpluses (Fig. 5b). Up to a certain proportion, the K budget can therefore be balanced by the use of multi-nutrient base fertilizers, while the remaining K demand can and should be complemented, e.g., by mineral K supplements. Overall, it can be concluded that nutrient imbalances are related to the disproportionate and unilateral use of specific fertilizers often used in organic vegetable production.

Fertilizer categories and N:P ratios for designing fertilizer strategies

In line with the previous considerations, the fourth research question addresses the relationship between fertilizer categories and N:P ratios in order to design balanced fertilizer strategies. Data from the present inventory suggest that a fertilization strategy that relies solely on one of the fertilizer categories described above can lead to long-term imbalances: the use of solid base fertilizers like composts, farmyard manures, or champost is prone to result in large P and K surpluses increasing the risk of long-term accumulation of these nutrients in the soil (Fig. 5a, b). In contrast, a fertilization strategy based on BNF and the use of keratins may lead to nutrient mining of soil P and K in the long run. The challenge is to design balanced fertilization strategies according to the nutrient offtakes considering the N value of the chosen fertilizers. For example, Fig. 6 highlights that the ideal N:P ratio for fertilizing vegetable crops with an N:P output ratio of an average of 5.75 (Fig. 3) (Möller 2018; Nelson and Janke 2007) is achieved when the share of N supply via keratin fertilizers together with BNF and via solid base fertilizers is close to 45% each. In this inventory, this is nearly achieved by Farms 5, 6, 7, and 12 (Fig. 2). However, three of these farms (Farms 5 to 7) show N surpluses above 70 kg N ha^{-1} far beyond an acceptable range, as previously stated (Table 4) (Oenema et al. 2015). These farms combine the use of solid manures or composts and keratins (Fig. 2). Solid manures and composts have high P and K contents in relation to N (Möller 2018). Combined with a low NUE, the risk of overfertilization with P and K increases, which may lead to their accumulation in the soil (Nelson and Janke 2007). The opposite is true for digestates: they combine a wider N:P ratio (Fig. 3) with a higher NUE (Möller 2018). Farm 12 is the only farm that uses biogas digestates (Fig. 2, over 40% of its fertilizer N input) and has the closest match regarding the N:P:K inputs and outputs via sold vegetables in the present study (Figs. 2 and 4). This could provide an indication that biogas digestates are well suited as a fertilizer source in organic vegetable production. However, while the EU organic regulation allows the use of biogas digestates as long as they do not include components from industrial animal husbandry ((EU) 2021/1165 2021), German organic associations still impose stronger restrictions on their use (Bioland 2023; Demeter 2023). As a result, digestates

are not yet widely used on organic vegetable farms. Overall, it can be concluded that not only the share of base fertilizers but also the type of base fertilizer plays an important role. To overcome the problem of nutrient imbalances, either fertilizers with an almost balanced nutrient composition and a high NUE (e.g., digestates) should be used or fertilizers with a complementary composition (e.g., solid manures high in P with fertilizers low in P like vinasse, keratins, or BNF) should be combined effectively. Any unilateral strategy based on the use of solid base fertilizers as often promoted in the organic farming community may lead to large P surpluses (e.g., when based on solid animal manures or composts), affecting the sustainability of the system when not complemented by appropriate inputs of N via keratins or BNF.

Conclusion

Organic vegetable farmers face at least two major challenges regarding their soil fertility management: implementing nutrient management that achieves balanced nutrient budgets and reducing N surpluses through more efficient use of internal and external N sources. The findings of this survey demonstrate that the implementation of fertilization strategies that address the three macro-nutrients N, P, and K simultaneously is very challenging when using organic fertilizers as multi-element sources with large differences in their nutrient stoichiometry. Any unilateral fertilization strategies are more likely to lead to nutrient imbalances with strong nutrient surpluses or deficiencies. Solid farmyard manures and champost have the lowest N:P ratio, which could lead to large P surpluses in the long run. In contrast, the frequently used keratin fertilizers are very low in P and K, increasing the risk of strong P and K deficits in the long term. Therefore, we recommend that farmers combine base fertilizers and N-rich keratin fertilizers for balanced soil fertility management, depending on their individual N:P:K harvest output. Alternatively, they could use biogas digestates which have nutrient ratios that fit very well with the offtakes of vegetables. Ideally, digital solutions, e.g., N-Expert by the Leibniz Institute of Vegetable and Ornamental Crops (Germany) or NDICEA by the Louis Bolk Institute (Netherlands), that combine nutrient budgeting with soil data and calculate farm-specific fertilizer combinations could help to solve the problem at the farm level. However, the current

debate on the restriction of the use of fertilizers from conventional farming may result in further restrictions on fertilizers, particularly those of conventional origin. This may lead to unilateral fertilization strategies that are more likely to lead to nutrient imbalances with large nutrient surpluses or deficiencies. Furthermore, the lack of a relationship between the volume of N inputs and overall productivity combined with a low nitrogen use efficiency in stockless organic vegetable production is surprising as the nutrient demand of vegetable crops is relatively high. This indicates a need for further research, in particular in relation to the environmental effects of organic farming and the debate on the yield gap between conventional and organic farming systems.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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