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Cultivation of fiber nettle (*Urtica dioica* L.) in an agroforestry system for peat substitution in horticulture

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The German Federal Government aims to drastically reduce or even ban the use of peat in growing media in commercial horticulture by 2030. The joined project "Development and evaluation of peat-reduced production systems in horticulture" (ToPGa) explores and evaluates the challenges and effects of the employment of peat substitutes for practical application. For this, a special focus is set on the evaluation of the renewable, locally grown resource fiber nettle (*Urtica dioica* L.) as a potential peat substituent. In this approach, three fiber nettle genotypes were established in an alley cropping agroforestry system. To evaluate the dependency of the nettle growth on genotype and distance to the tree line, nettle yield was determined over four consecutive years. The differences in yield between different genotypes were not significant in first three years of harvest. In general, genotype L18 showed a higher biomass yield as B13 and Z10. The yield of nettles growing 6 to 12 m from the tree line was significantly higher. We conclude that while all genotypes can tolerate the growing conditions close to the trees, nettle plants gain higher yields when grown further from the tree line with a maximum yield of 11.4 t ha^{-1} in the fifth year of cultivation. Retted nettle exhibits a low pH and minimal salinity. Nettles accumulate only low amounts of trace elements. Overall, chemical properties vary according to the season of harvest. Annual variations in retted material are not significant.

KEYWORDS
agroforestry, fiber nettle, yield, peat substituents, fertilization, trace elements

1 Introduction

In Europe, political activities are currently underway in Germany, Ireland, the Netherlands, Norway, Switzerland and the UK to reduce the use of peat in horticulture in an attempt to mitigate further greenhouse emissions (Hirschler et al., 2022). In Germany, the German Federal Ministry of Food and Agriculture (BMEL) launched a peat reduction strategy that aims to reduce or replace peat in horticultural substrates in the hobby gardening sector by 2026 and in the commercial horticultural sector by 2030 (BMEL, 2022).

As peat mining has become more restricted to conserve natural and near-natural peatland and mitigate climate change, the search for new peat substituents is detrimental for horticultural substrate manufacturers to persist. However, potential peat substituents have to exhibit suitable physical and chemical properties to support optimal plant growth, while their quality has to be certified, consistent and their availability should not compete with their use in other economic sectors (Hirschler and Thrän, 2023). Recently, the sustainability of the potential resource and their ensured long-term availability have become of special interest in the search for new substituents. The research project ToPGa (Development and evaluation of peat-reduced production systems in horticulture) is investigating, inter alia, the use of as of yet unknown regionally grown resources, such as the fiber nettle (Julius Kühn-Institute, 2021).

The fiber nettle is a variety of the stinging nettle (*Urtica dioica* L. convar. *fibra*), whose fiber content has been increased through breeding different wild types (Bredemann, 1959). Until the middle of the last century, the fiber nettle was a popular plant widely used in the textile industry of Germany and Austria (Vogl and Hartl, 2003). Yet, with the rise of synthetic fibers and low-cost cotton, the commercial cultivation of fiber nettle was neglected (Viotti et al., 2022). More recently, the interest in cultivating fiber nettle, hemp or flax has returned due to the growing demand for more sustainable textiles in the public mind. Most of the genotypes currently on the market, which were reintroduced in 1993, can be traced back to the breeding efforts of Bredemann (Dreyling, 2002). Yet, it is still common practice to propagate fiber nettle vegetatively by stem cuttings, as there are no known working methods of using somatic embryogenesis for commercial nettle reproduction (Fischer et al., 2019).

As a perennial plant, nettle can be cultivated extensively (Di Virgilio et al., 2015). The plants can grow on various soils with differing qualities without an intensive input of pesticides, herbicides, fertilization or irrigation. Although they perform better on nutrient-rich soils with regular irrigation, they may also be able to grow on less productive marginal soils (Fischer et al., 2019; Viotti et al., 2022). Since nettles are nitrophilous plants, they may be able to improve soils with an unhealthy abundance of nitrates and phosphates (Di Virgilio et al., 2015). Depending on the availability of water, nettle can grow well even at cooler temperatures that are prevalent in the temperate climate of Northern Europe (Viotti et al., 2022). With proper weed management, commercial harvest of nettle plants is possible for at least five years (TLLLR, 2021) or up to ten years (Vogl and Hartl, 2003). The cultivation of nettle genotypes with a high yield and fiber content allows for a high biomass production. Although the cultivation of the fiber nettle has its benefits, the lack of interest in the use of the fiber nettle material means that their current cultivation depends strongly on the demand for nettle. At present, in Germany nettle is mostly cultivated for its use as a medicinal or spice plant (TLLLR, 2021). Cultivating nettle for fibers is still only profitable with a prior contract with a processor (contract farming).

Our research is based on the idea of a two-way usage of the fiber nettle plant: during their processing, the fibers are separated from the woody components (shives). To reduce the generation of waste products, fibers would be used for the production of textiles, and shives as a potential new peat substitute. Alternatively, some recent studies reported the development of biocomposites produced from nettle fiber (Mudoi et al., 2021; Andrew and Dhakal, 2022). For this study, three commercially available fiber nettle genotypes were established in an alley cropping agroforestry system between a poplar tree strip and a crop strip. In nature, nettles are often associated with poplars or willows in riparian habitats (Viotti et al., 2022). The yield of annual field crops is reduced in a zone close to the tree strips due to competition for resources such as light, water and nutrients (Swieter et al., 2019; Taylor, 2009). Being shadow-tolerant, we assumed that nettle yield would not be reduced. Therefore, the dry mass yield of the nettle plants was determined each year in late summer at the end of their growing period from 2021 to 2024. Initial experiments in the ToPGa-project showed that the chemical properties of shives from nettles harvested in summer do not suit plant growth when mixed into horticultural substrates. As a result, harvesting to obtain shives for the production of peat substitutes took place in winter after a long retting period on the stalk. This study aimed to examine (i) the dry matter yield of three fiber nettle genotypes over four years after establishment in an agroforestry system in Northern Germany, and (ii) to analyze the chemical properties of fiber nettle shives after field retting over the winter period.

2 Method

Three fiber nettle genotypes (B13, L18 and Z10) were implemented in an already existing alley cropping agroforestry system in Wendhausen (Lehre) close to Braunschweig (52° 20'00.8"N 10°37'57.9"E) on a vertic cambisol soil. Fiber nettles were obtained as vegetative young plant shoots propagated through cutting from the Institute for Plant Culture GmbH & Co. KG (Schnega, Germany). Nettles were planted by hand at a plant density of 25,000 plants/ha (0.53 x 0.75 m) on two field plots of 100 x 12 m in June 2020 (Figure 1). Each field plot bordered on a 12 m wide poplar tree strip on one side and on a 24 m wide crop strip with an alternating crop rotation (oilseed rape, corn, summer barely) on the other side. Nettles were planted in four randomized complete blocks within plots of 8 x 12 m each. Genotypes were randomly assigned to the "field" (1–6 m) and "tree" (6–12 m) position in each block (Figure 1). Tree height was between 2.5 m in 2021 and 6 m in 2023. At the beginning of each growing period (April) the fiber nettles were fertilized with 8 dt ha^{-1} NovaTec® Classic 12-8-16 (+3 + 10) fertilizer, which culminates to an amount of 100 kg N ha^{-1}. After planting, the seedlings were watered by hand regularly; later the only irrigation source was rainfall. Throughout the growing season, the height of developing nettles was measured manually with a folding ruler occasionally and at random (data not shown).

For the yearly dry matter yield estimation, a transect (1.5 x 6 m) across the entire width of each plot was harvested with a brush cutter in early September from 2021 to 2024. Harvesting took place

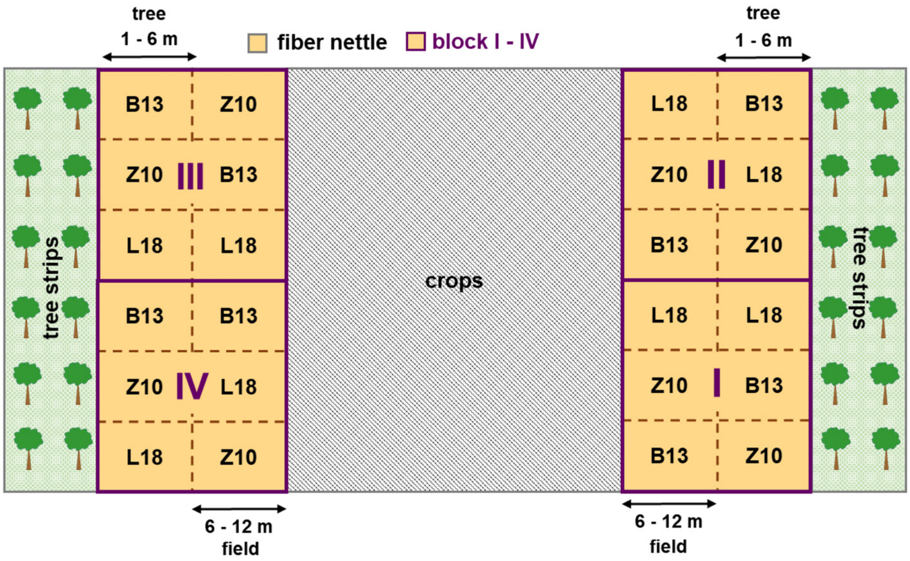

FIGURE 1
Cultivation of fiber nettle in the alley cropping agroforestry system Wendhausen (Lehre, Lower Saxony). Each nettle genotype (B13, L18 and Z10) is planted in each block (I-IV, purple) both in the "tree" (i.e. 1–6 m distance to tree strip) and the "field" (6–12 m distance to tree strip) position.

after flowering, thus the dry matter yield was made up of stalk and leave mass. Dry matter yield of each sample was determined after drying at 105°C for 24 h. For the investigation of fiber nettle shives as a peat substitute, shives were obtained from both, the harvest in September (just 2022) and after field retting on the stalk over winter in January (2022-2024). For this, retted nettle was harvested by hand or a bar mower (AGRIA-Werke GmbH). After harvest, the nettle was dried and shredded by a forage harvester (Pöttinger Landtechnik GmbH). Then, nettle shives and fibers were separated by a roll-sieve of 1 x 1 cm (Scheppach GmbH).

The suitability of nettle shives as peat substitutes was evaluated based on relevant chemical properties such as carbon and nitrogen content. For the analysis, nettle shives were ground to one-millimeter particles using a rotary mill (Brabender, Anton Paar TorqueTec). The carbon and nitrogen content (C:N ratio) was determined using a CNS Analysator vario max cube (Elementar Analysensysteme GmbH) according to the Dumas-method (VDLUFA, 2004). Furthermore, the pH value and the salinity of the nettle shives were assessed (VDLUFA, 2016, 1997). The concentration of available micronutrients and trace elements, such as P, K, Ca and Mg were analysed by microwave digestion using the Start 1500 (MLS) and inductively coupled plasma optical emission spectrometry (ICP-OES-CAT) using the Thermo Icap 6300 Duo (Thermo Scientific) (VDLUFA, 2002).

Data analysis was performed with RStudio (R Core Team, 2024). For evaluation of dry matter yield, generalized linear mixed effect models were fitted with the position (field, tree), the cultivation year (2021-2024) and the genotype (B13, L18, Z10) as fixed effects and the block as random effect. The package glmmTMB (Brooks et al., 2017) was used; the dependence of the yield on the previous year's yield of the perennial nettle with the function ar(1) was taken into account. After automated model selection (Barton, 2023), final models were selected based on the lowest Akaike information criterion (AIC). Subsequent analyses of variance (ANOVA type II) were followed by *post-hoc* comparisons of means using the emmeans package (Lenth et al., 2024). All data were square root transformed to achieve homogeneity of variance. Significance level for analysis was set at $p < 0.05$.

3 Results

Nettle dry matter yield was significantly influenced by the position (distance to the tree line) and the year. Dry matter yield was significantly higher in plots with a distance of 6–12 m to the trees compared to nettle grown in plots 1–6 m near the trees (Figures 2A, B). Dry matter yield was lowest in the first two years after the establishment of the nettle with an estimated mean of 1.97 t ha^{-1} in 2021 and 2.03 t ha-1 in 2022. In 2023 and 2024, significantly higher yields were determined. With an estimated mean of 6.43 t ha^{-1}, the dry matter yield in 2024 was nearly twice as high as in 2023 (3.48 t ha^{-1}) and three times higher than in 2021 and 2022, respectively (Figures 2A, C). Thistles (*Cirsium spec.*) growing inside and along the fiber nettle population drastically reduced the growth of the neighbouring nettle plants. The contaminated parts of the nettle population could not be harvested, neither for yield estimation nor for processing as a peat substituent.

Although there was no significant effect of the genotype on the nettle dry matter yield, yield of genotype Z10 was tendentiously overall the lowest and the yield of L18 the highest (Figure 3). In 2021 and 2022, the yields of all three clones were similar. With a mean of 7.12 t ha^{-1} (B13), 9,47 t ha^{-1} (L18) and 5.72 t ha^{-1} (Z10), the dry matter yield of all genotypes in 2024 was almost twice as high as in 2023 (Figure 3). During the growing season, the heights of the different nettle genotypes were measured. Since the measurements were taken at random over the years of cultivation, only an estimate

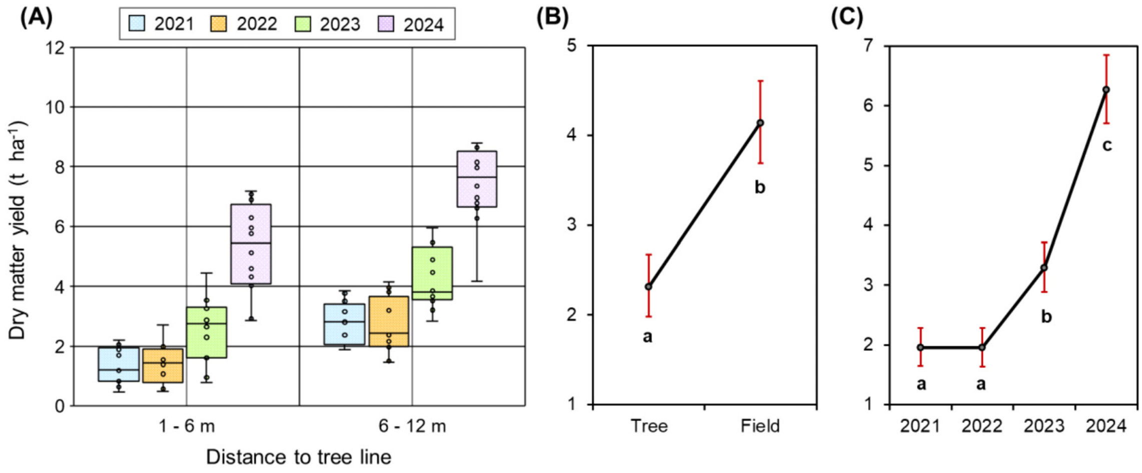

FIGURE 2
Influence of tree line distance and the year on fiber nettle dry matter yield in the alley cropping agroforestry system. **(A)** Boxplots with overlaid scatter plots showing the dry matter yields in the position “tree” (1–6 m) and “field” (6–12 m) in the years 2021 to 2024, **(B)** estimated mean dry matter yield at the position “tree” and “field”, **(C)** estimated mean dry matter yield in the years 2021 to 2024. In figures **(B, C)**, error bars are the confidence intervals of the candidate model with filled squares as predicted mean values. Lowercase letters show significant differences ($p < 0.05$) between dry matter yield values.

of the approximate heights reached by the nettles can be given. Overall, both B13 and L18 were taller (over 200 cm) and had thicker stems than Z10 (under 200 cm). On the other hand, Z10 developed much more pronounced leafy side branches than the other two genotypes.

In a separate experimental approach, we investigated the influence of nitrogen fertilization on the yield of genotypes in Braunschweig (52°18’01.7”N 10°26’24.6”E) from 2022 to 2023 (Supplementary Figure S1). An average dry mass yield of 3.3 (fertilized with 50 kg N ha^{-1}), 4.8 (100 kg N ha^{-1}) and 7.9 t ha^{-1}

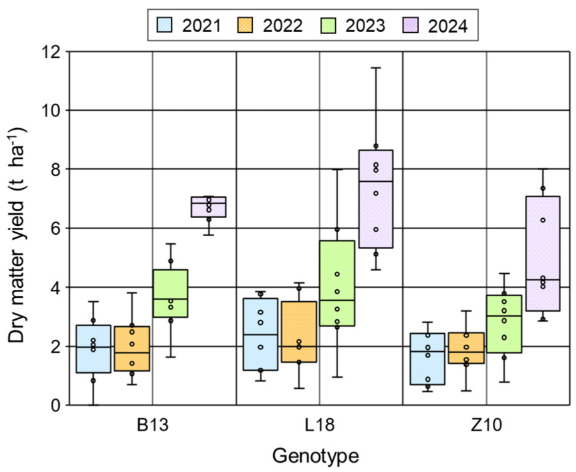

FIGURE 3
Influence of the genotype (B13, L18 and Z10) on the fiber nettle in the alley cropping system. Boxplots with overlaid scatter plots showing the dry matter yields of the genotypes B13, L18 and Z10 from 2021 to 2024.

(150 kg N ha^{-1}) were reached in the first cultivation year. In the second cultivation year, yields with an average of 5.7 (with 50 kg N ha^{-1}), 6.5 (with 100 kg N ha^{-1}) and 7.9 t ha^{-1} (150 kg N ha^{-1}) were achieved. During the two-year period, only the dry matter yield differed significantly between the applied fertilizer rates of 50 and 150 kg N ha^{-1} (Supplementary Figure S1).

The analysis of processed fiber nettle shives showed that the properties of the material were strongly dependent on the season of the harvest. Nettle shives harvested in January generally had a higher C:N ratio (> 70), a lower pH value (< 7,0) and lower salinity (< 0.3 g KCl/l) than nettle shives harvested in September (Table 1). The data suggest that the concentration of trace elements such as iron and manganese varies greatly depending on the year of harvest, while the concentration of the minerals such as sodium, magnesium, phosphor and potassium varies depending on the year of harvest and the season of harvest (Table 1). Nettle shives harvested in September contain a higher amount of plant-available nutrients than those harvested after retting in January. In comparison to the other minerals, potassium was accumulated in the highest concentration in all samples (> 874 mg K/kg).

4 Discussion

The undemanding nature of fiber nettle is the main advantage in growing this plant in an alley cropping system. Although considered shade-tolerant, yield of nettles cultivated one to six meters near a tree strip was significantly reduced. It has already been shown for several field crops that yield is reduced in the area close to the tree strip (1–7 m, Swieter et al., 2019) due to competition for resources like light, water, nutrients and space. Moreover, weed contaminations (e.g. grasses) can seriously inhibit

TABLE 1 Chemical properties of the fiber nettle shives for use as a peat substituent.

Time of harvest	C:N	pH ($CaCl_2$)	Salinity (g KCl/l)	Mn (mg/kg)	Fe (mg/kg)	Na (mg/kg)	Mg (mg/g)	P (mg/g)	K (mg/g)
January 2022	97	6.6*	0.2	28	40	114	247	510	1317
September 2022	30	7.8	0.7	55	22	175	1198	1065	21289
January 2023	69	6.3*	0.3	54	22	169	539	403	874
January 2024	84	6.7*	0.0	51	8	110	547	724	1167

Genotypes, i.e. B13, L18 and Z10, harvested in January 2022 were mixed before analysis. Genotypes harvested in September were analysed separately, a mean value across genotypes is shown. * provided by Leibniz University Hannover, Institute of Earth System Sciences, Section of Soil Science.

fiber nettle growth (Vogl and Hartl, 2003; Di Virgilio et al., 2015). This was observed in our alley cropping system with mainly thistle.

4.1 Effects determining fiber nettle dry mass yield

The mean dry matter yield over all clones was relatively low with approximately 2 t ha^{-1}in the first and second year after establishment. As reported by Hartl and Vogl (2002), low yields are to be expected in the first year of cultivation. Low yield in the second year of cultivation (2022), was attributed to a heat period in 2022 (Daily maximum 38.3° C, 1507 h of sunshine; DWD Climate Data Center, CDC, 2024a, 2024b) with a severe drought with just 122 mm of rain between March 1 and August 31 (Callejas Rodelas et al., 2025). This amounted to less than half the long-term precipitation of the years 1991 to 2010 (340.4 mm; DWD Climate Data Center, CDC, 2024c). Nettles can grow under less than beneficial conditions, nevertheless they will benefit from regular irrigation, especially in their main growing phase in spring (Jeannin et al., 2020; Di Virgilio et al., 2015). In the third cultivation year, mean estimated dry matter yield increased to 3.3 t ha^{-1}. Similarly, Hartl and Vogl (2002) observed an increase in yield between the second and third year of cultivation. Fischer et al. (2019) also reported that once nettle plants are established, an increase in yield could generally be expected in later years of cultivation. Their study also confirmed that extreme climatic conditions, like floods or droughts, could have a negative effect on nettle growth and thus on annual yield. In this study, the yield increase in 2023 was attributed to more favourable climatic conditions. Compared to 2022, both precipitation and temperature were over the long-term average from 1961 to 1990 in their growing period from March to August (351 mm, Callejas Rodelas et al., 2025; daily maximum 33.3°C, DWD Climate Data Center, CDC, 2024a).

In the present study, the three genotypes differed in morphology and heights. In the alley cropping system, the effect of genotype on yield was not noticeable until the third year of cultivation. No information from the breeder about the expected dry matter yield of L18 was available, but their data sheets indicated that Z10 can potentially reach higher yields than B13 (personal communication, Institute for Plant Culture GmbH & Co. KG). Fischer et al. (2019) studied the development of fiber nettle genotypes L2, L6, L18 and Z10 on two different soil types. They reported that both L18 and Z10 produced the highest yield and plant heights compared to the other genotypes. The differences between the yield of L18 and Z10 seemed also to depend on the annual climate conditions (Fischer et al., 2019). The extent of the influence of the fiber nettle genotype on the dry matter yield greatly varies from study to study. Depending on soil and climatic conditions, the planting density and the N-fertilization, dry matter yields of different nettle genotypes varied between 1.75 t ha^{-1} up to 15.42 t ha^{-1} (Viotti et al., 2022). This is supported by own experiments with B13, L18 and Z10 being cultivated on a loamy sand soil in Braunschweig (Supplementary Figure S1). Here, genotype B13 showed higher yields than L18 and Z10. This suggests that the yield of each genotype is indeed strongly influenced by local climate and soil conditions, as well as by the cultivation methods used.

Fiber nettle is a nitrophilous plant (Viotti et al., 2022). Thus, its growth benefits from an additional N-fertilization. Recommended N-fertilizer rates vary from study to study: some reported dry stalk yields of 9.81 to 12.85 t ha^{-1} by applying 200 kg N ha^{-1} (Bacci et al., 2009), whereas others reached similar yields without any N-fertilization (Schmidtke et al., 1998). The Thuringian State Office of Agriculture and Rural Areas (TLLLR, 2021) recommends a fertilization rate of 200 kg N ha^{-1}, while other authors recommend significantly lower amounts of fertilization with a rate of 60–80 kg N ha^{-1} (Dreyer and Müssig, 2000). In the present study, the fiber nettles in the alley cropping system were fertilized with an amount of 100 kg N ha^{-1}, this resulted in yields similar to other studies (Viotti et al., 2022). We observed that fiber nettle plants near the crop field tended to develop more biomass, perhaps because fertilizer from the crop strip reached the nettles. In the Braunschweig field trials, the effect of nitrogen fertilization rates on nettle yields in 2022 or 2023 varied (Supplementary Figure S1). The data suggest that lower fertilizer rates may be feasible for our fiber nettle cultivation without much yield loss, while higher fertilizer rates could potentially increase the yields further. However, longer trials are needed to confirm these observed fertilization effects on nettle yield growth.

Regardless of nitrogen fertilization, the nettle yield in Braunschweig was higher than in the alley cropping system in Wendhausen in 2022 and 2023. The yield differences are probably due to the different soil type and the possibility of irrigation in Braunschweig. Nettle prefer loose, nutrient rich soils with a good water accessibility for optimal biomass production (Di Virgilio et al., 2015; TLLLR, 2021). Their growth can be drastically inhibited by heavy rain periods (Fischer et al., 2019) or floods (Jankauskienė and Gruzdevienė, 2015; Taylor, 2009). Analogously, nettle in Braunschweig showed a delayed growth accompanied by strong weed contaminations after a heavy rain period with floods in December 2023 to January 2024 (191 mm; DWD Climate Data Center, CDC, 2024c). They did not recover their growth from previous years, resulting in visible gaps in the crop.

4.2 Nettle properties influence suitability in replacing peat

In this project, fiber nettle is cultivated to use their processed shives as a potential peat substituent. Chemical properties of the material determine their quality and therefore the quality of the potential substrate mixture. To evaluate their potential as a peat substituent, only specific parameters were of interest (Stucki et al., 2019). The carbon: nitrogen content can be used to assess decomposability of the nettle shives. N-immobilization in a horticultural substrate is a major concern as it leads to complications in plant growth or even yield loss (Gruda et al., 2000). A narrow C:N ratio signifies a faster material degradation through a higher microbial activity, but also a source of plant-available nutrients, like e.g. nitrogen or potassium. While a wide C:N ratio alludes to lower decomposability rate and in consequence lesser amounts of nutrients are available for plants from the material (Schmilewski, 2003; Stucki et al., 2019). To minimize potential N-immobilization, peat substituents with a narrower C:N ratio are favoured. Otherwise, an addition of nitrogen through fertilization may reduce N-immobilization in substrates with a wider C:N ratio (Gruda et al., 2000). For the support of optimal plant growth in the substrate, the peat substituent should have a slightly acidic pH value (pH 5.5-6.5) and low salinity (1.0-2.5 mS/cm, Fuchs, 2001; Stucki et al., 2019; Leiber-Sauheitl et al., 2021).

The chemical properties of the nettle shives were strongly affected by the time of harvest. Nettle shives harvested in summer had a C:N ratio comparable to peat (Schmilewski, 2003), while their alkaline pH value and the high salinity could be detrimental to plant growth. After field retting, the amount of nitrogen decreases through microbial degradation, which leads to a higher C:N ratio and a higher risk of N-immobilization in the substrate. However, as most peat-free substrates are mixtures of a variety of different constituents, any possible negative impacts of one material can be minimized by reducing its proportion in the substrate. The retting process in the field influenced the salinity and the concentrations of accumulated plant-available nutrients through leaching over time. Phosphorus and potassium are accumulated in the highest concentrations, as fiber nettle - besides nitrogen - also requires both for optimal growth (TLLLR, 2021; Pigott, 1971). In their study about a contaminated short rotation coppice, Jeannin et al. (2020) concluded that nettle is not a hyper-accumulator like other woody species or other hyper-accumulators like hemp. These results where corroborated by our data and by Sahiti et al. (2023). However, some pot experiments with *Urtica dioica* L. showed that nettle did accumulate higher amounts of heavy metals (Shams et al., 2010; Viktorova et al., 2016). The ability of fiber nettle to accumulate micronutrients, such as phosphate, or heavy metals need be investigated further to fully assess the potential of this plant in phytostabilization practices (Jeannin et al., 2020; Viotti et al., 2022) or the long-term effects on soil health. Currently, there are no studies published concerning long-term environmental impacts of nettle cultivation. In surveys of our alley cropping agroforestry system into the carbon distribution and content of the root system, fiber nettle roots were observed in depth of 160 cm (Schmiedgen et al., 2024). The findings suggest that the cultivation of the perennial fiber nettle can contribute to a long-term CO_2 fixation, while also minimizing soil erosion.

To conclude, our findings confirm that fiber nettle can be cultivated successfully in an alley cropping agroforestry system with yields comparable to those reported in literature. The dry matter yield in a zone up to six meters next to the tree line is significantly reduced, while maximum yields are recorded in the area of the field not affected by the trees. This leads to heterogeneously distributed yields across the fields on the alley cropping system. The genotype can influence the yield, but the impact of its effects may depend on other factors like soil type, irrigation, fertilization, annual climate conditions and weed management. Quality analysis has shown that shives from the winter harvest following a retting period on the stalk have a greater potential as a peat substitute than those from the summer harvest, as the former have a low salinity and a peat-like pH value. The suitability of fiber nettle shives as a peat substituent in horticultural growing media still needs to be verified in horticultural growth experiments.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LL: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Visualization, Writing – original draft, Writing – review & editing. DK: Formal Analysis, Investigation, Writing – review & editing. ML: Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1570902/full#supplementary-material

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