Cleaner and Circular Bioeconomy 13 (2026) 100199

Contents lists available at ScienceDirect

Cleaner and Circular Bioeconomy

journal homepage: www.elsevier.com/locate/clcb

Leveraging regionally sourced natural fibers for coreless filament winding in sustainable construction

Alina J. Rossa [a,b,*], Daniel Christopher Bozó [a,c,1], Pascal Mindermann [a,c,1], Götz T. Gresser [a,c,d], Franziska Schuenemann [a,b]

[a] Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC), University of Stuttgart, Keplerstraße 11, 70174 Stuttgart, Germany
[b] Institute for Economics, Department of Bioeconomy, University of Hohenheim, Wollgrasweg 49, 70599 Stuttgart, Germany
[c] Institute for Textile and Fiber Technologies, University of Stuttgart, Pfaffenwaldring 9, 70569 Stuttgart, Germany
[d] German Institutes of Textile and Fiber Research, Denkendorf. Körschtalstraße 26, 73770 Denkendorf, Germany

ARTICLE INFO

Keywords:
Natural fibers
Biobased construction
Coreless filament winding
Regional bioeconomy
Biocomposites

ABSTRACT

This study investigates the potential of regionally sourced natural fibers (NF) as sustainable feedstocks for coreless filament winding (CFW), an innovative and resource-efficient composite fabrication method for construction. As the sector moves towards bio-based materials, flax has emerged as a benchmark due to its compatibility with CFW and favorable mechanical properties. However, supply chain vulnerabilities and price volatility highlight the need for regional alternatives to flax fibers. By assessing hemp, miscanthus, lavender, nettle and wheat straw cultivated in Baden-Württemberg (BW), this paper links crop sustainability and fiber suitability with the broader aim of strengthening local biomass utilization within the bioeconomy. A multi-stage evaluation framework compares environmental, economic, social, and technical indicators against flax, focusing on biomass availability, input intensity, ecosystem services, land-use competition, and fiber properties. The results identify hemp as the most promising alternative due to its high fiber output, low cultivation inputs, beneficial ecosystem services and mechanical performance. Nettle offers strong mechanical performance but faces agronomic limitations, while lavender presents niche potential under integrated production systems. Miscanthus and wheat straw, while unsuitable for direct CFW due to fiber morphology, may serve as supplementary feedstocks through modified processing. These findings underscore the role of local biomass streams in creating robust regional value chains, contributing to the resilience and sustainability of the bioeconomy. While the focus of this study is on BW, the framework can be transferred to other regions and may serve as a practical tool for policy, industry, and research seeking to advance circular approaches in bio-based construction.

1. Introduction

The construction industry is seeking ways to minimize its environmental impact. Two key strategies are the increase of material efficiency and the reduction of the environmental footprint of raw materials. Research by the Integrative Computational Design and Construction for Architecture cluster (IntCDC) at the University of Stuttgart, Baden-Württemberg (BW), Germany, has successfully combined both approaches by manufacturing natural fiber based structures with coreless filament winding (CFW) (Carosella et al., 2024). CFW is an advanced manufacturing technique used to create lightweight, material-efficient composite structures without the need for a core or mandrel. Fibers impregnated with resin are wrapped around clusters of spatially arranged anchor points (Mindermann and Gresser, 2023) in a controlled sequence (Mersch et al., 2025), gradually building up a structure layer by layer. Once cured, the result is a load-bearing component with minimal material waste (Gil Pérez and Knippers, 2023). A key advantage of CFW is its ability to reduce material consumption by strategically placing fibers only where they are needed for structural performance (Gil Pérez, 2024). By eliminating excess material and reducing reliance

List of Abbreviations: BW, Baden-Württemberg; CFW, Coreless Filament Winding; CV, Coefficient of Variation; FVR, Fiber Volume Ratio; IntCDC, Cluster of Excellence Integrative Computational Design and Construction for Architecture; NF, Natural Fibers; THC, Tetrahydrocannabinol.

* Corresponding author.
E-mail address: alina.rossa@uni-hohenheim.de (A.J. Rossa).

[1] These authors contributed equally.

https://doi.org/10.1016/j.clcb.2025.100199
Received 10 November 2025; Received in revised form 18 December 2025; Accepted 18 December 2025
Available online 19 December 2025

on energy-intensive molds, the process contributes to overall sustainability in composite manufacturing. Moreover, the method is compatible with a wide range of fibers (Mindermann et al., 2022b), including both synthetic and natural options.

Past projects using natural fibers (NF) have primarily relied on flax fibers due to their fabrication suitability and mechanical performance (Mindermann et al., 2022b). However, supply chain constraints and price volatility (CELC, 2024) raise concerns regarding future material availability and cost. While flax remains an established reference, the long-term development of bio-based composites in construction will require a broader set of fibers. Current studies on NF composites often concentrate on specific parameters such as mechanical properties (Elfaleh et al., 2023; Harish et al., 2009; Summerscales et al., 2010), life-cycle impacts (Deng and Tian, 2015; Gomez-Campos et al., 2021; Ramesh et al., 2022), and general application potential (Ahmad et al., 2015; Dittenber and GangaRao, 2012; Gurunathan et al., 2015), without a multi-dimensional sustainability assessment. In addition, these studies primarily examine globally prominent fibers such as flax, hemp, jute, sisal, and coir, overlooking region-specific availability (Bogard et al., 2022; Chang et al., 2020; Dicker et al., 2014). Local availability significantly influences the environmental performance and economic viability of bio-based raw materials such as NF, making less common but regionally grown fiber plants particularly relevant (Harish et al., 2009; Ismail et al., 2011). Yet, there is a lack of systematic knowledge about whether regionally available crops can provide sustainable and technically suitable alternatives to flax. Possible alternative fiber crops suitable for cultivation in BW are those that thrive in a mild climate, yet can stand occasional heat and dry spells, while remaining resilient to cold spells. Many of the common plant-derived fibers such as jute, sisal and coir therefore do not present viable alternatives to flax as they cannot grow under these climatic conditions. Flax (Linum usitatissimum L.) is an annual crop originating from the Middle East, historically cultivated widely in BW over the last century (Manian et al., 2021; FNR, 2008). It is sensitive to both water scarcity and excess (Grundmann, 2009; Sazzini, 2024) and is used in textiles, food, and composite applications (FNR, 2008), with well-established commercial yarn production (CELC, 2024). This assessment considers five alternative fiber crops:

(1) Hemp (*Cannabis sativa L.*) is an annual crop originating from China, adaptive to a range of climatic conditions but moderately drought sensitive (Adesina et al., 2020; Barth, 2015; Cherney and Small, 2016; FNR, 2008). Hemp fibers are used in food and feed, textiles, and composites (FNR, 2008). Commercial yarn production from hemp fibers is well established (CELC, 2024). Cultivation in the European Union is permitted under strict regulations regarding approved seed varieties and tetrahydrocannabinol (THC) content below 0.3 % (BMEL, 2023).

(2) Miscanthus (*Miscanthus x giganteus*) is a perennial grass originating from East Asia, propagated via rhizomes rather than seeds, with an expected lifespan of approximately 16 years (Lewandowski et al., 2000; KTBL, 2024a; Witzel and Finger, 2016). It is robust across a wide range of climatic conditions but thrives especially in temperate climates. It is primarily used for biomass and bioenergy and does not have established commercial yarn production.

(3) Lavender (*Lavandula angustifolia Mill.*) is a perennial crop native to the Mediterranean region, preferring warm, dry climates with little frost and well-drained soils (Bashyal, 2024; McCoy and Davis, 1999). Cultivated mainly for essential oil, ornamental, cosmetic, and pharmaceutical purposes (Lesage-Meessen et al., 2018), fiber extraction from residues of essential oil production is feasible, but commercial yarn production is not yet established (Biopro, 2023).

(4) Stinging nettle (*Urtica dioica L.*) is a perennial European fiber crop that grows best in temperate climates on moist, nitrogen-rich soils (Bacci et al., 2009; TLLLR, 2021). It is used in textiles and pharmaceuticals and is related to ramie, a fiber commonly used in biocomposites (Bogard et al., 2022; Koronis et al., 2013; Dicker et al., 2014; Gurunathan et al., 2015). While nettle is a historically well-established textile crop, its commercial yarn production today is limited to small-scale operations (Vogl and Hartl, 2003; TLLLR, 2021).

(5) Wheat straw (*Triticum* spp.) is an annual crop originating from the Middle East, growing under temperate conditions but sensitive to drought and heat (Becker et al., 2025; Curtis et al., 2002; Velimirovic et al., 2021). It is primarily used for food and feed, biomass, and paper production (Panthapulakkal et al., 2006). Its potential as a fiber source is being researched, since it is a widely available resource (BIOCOM, 2022).

This study applies a multistage framework that integrates economic, environmental, social, and technical criteria. The specific aim is to identify regional fiber crops that can serve as alternatives to flax fibers in CFW for construction applications, with the evaluation grounded in intrinsic fiber properties rather than existing processing maturity and infrastructure. To this end, the study compares the suitability of fiber crops regional to BW, Germany, while also developing a methodological approach that links sustainability performance with technical processability. In doing so, the study clarifies which fibers represent viable alternatives and how such assessments can be carried out in a systematic and transferable way.

2. Method

A systematic approach to assess the sustainability and suitability of regional NF is employed, see Fig. 1. The assessment focuses on cultivation and the intrinsic properties of the fibers. Extraction and processing are beyond the scope of this study, as little to no regional processing infrastructure currently exists for any of the considered fiber crops, regardless of their maturity or commercial use. The main aim is to identify suitable alternatives to flax, including under-researched crops with potential for future development.

The methodology consists of the following steps: (1) identifying fiber crops suitable for cultivation in BW, (2) selecting sustainability and suitability criteria based on an extensive literature review, (3) compiling a refined set of evaluation metrics for data collection, and (4) benchmarking the selected fibers against flax as a reference material.

2.1. Fiber crop selection

The first step in the framework is the selection of fiber crops to be included in the assessment. This establishes the scope of the study and ensures that the analyzed crops are both regionally relevant and potentially suitable for use in CFW. In this context, the term natural fiber refers to plant fibers only, excluding mineral and animal fibers. The suitability of potential fiber crops is primarily based on the agro-ecological conditions in BW, which determine both climatic feasibility and expected cultivation performance.

The state of Baden-Württemberg (BW) in Germany is situated in Central-Western Europe within the temperate climate zone (Pfeifer et al., 2021). Average temperatures have risen from 8.4 °C in the reference period 1971–2000 to 9.3 °C in the years 1994–2023, with further warming expected (Pfeifer et al., 2021; UMBW, 2023). This development is accompanied by an increase in the number of hot days above 25 °C and tropical nights. Frost days still occur but have become less frequent (UMBW, 2023). The long-term annual mean precipitation was approximately 957 mm between 1971 and 2000 (Deutscher Wetter Dienst, 2024). Considering climate change, winters are projected to become milder and wetter, whereas summers are expected to be drier and hotter. In addition, the frequency of extreme weather events, such as droughts, heavy rainfall and hail, is increasing. The changes in climate present both opportunities as well as challenges for agricultural

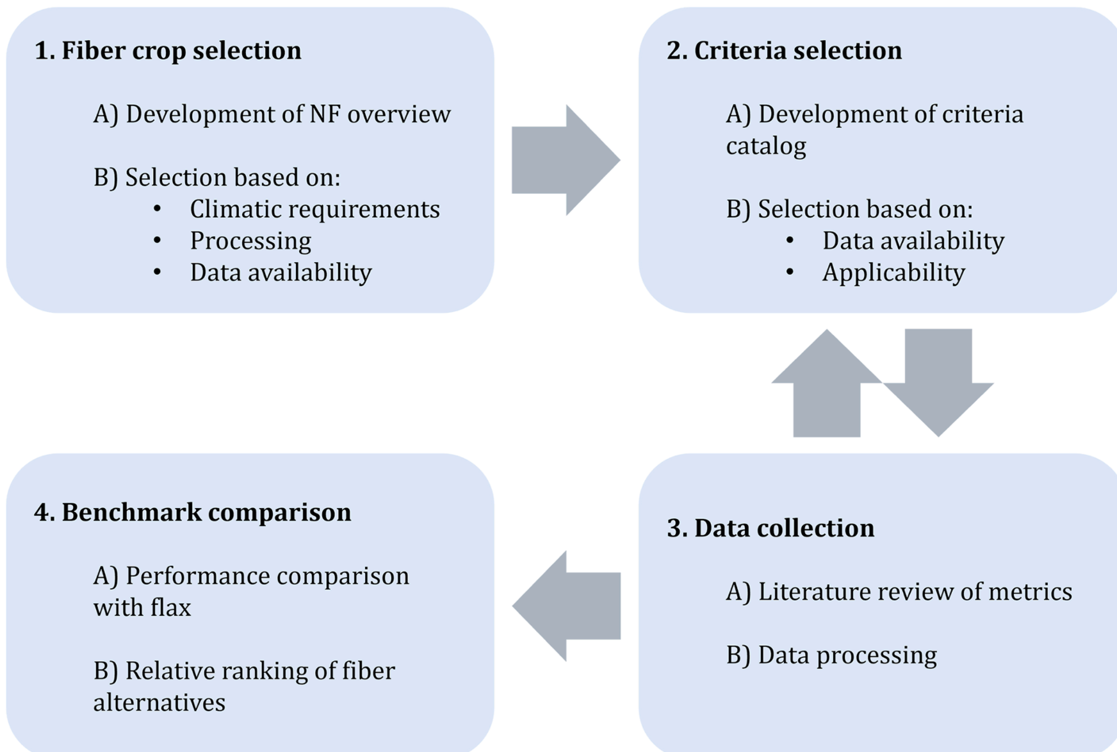

Fig. 1. Overview of the applied framework.

activities and influence crop choices. Warmer temperatures and longer vegetation periods (Pfeifer et al., 2021) can support crops with higher heat requirements. At the same time, the combination of summer drought risk, uneven precipitation, and more frequent weather extremes raises the importance of crop robustness. Since frost events continue to occur, crops grown in BW still need a certain level of frost tolerance, particularly in early growth stages.

Soil conditions vary, with BW being divided into 26 large soil regions that reflect geological and climatic patterns as well as long term land use (LGRB, 2025). Loess derived soils dominate many lowland areas. They

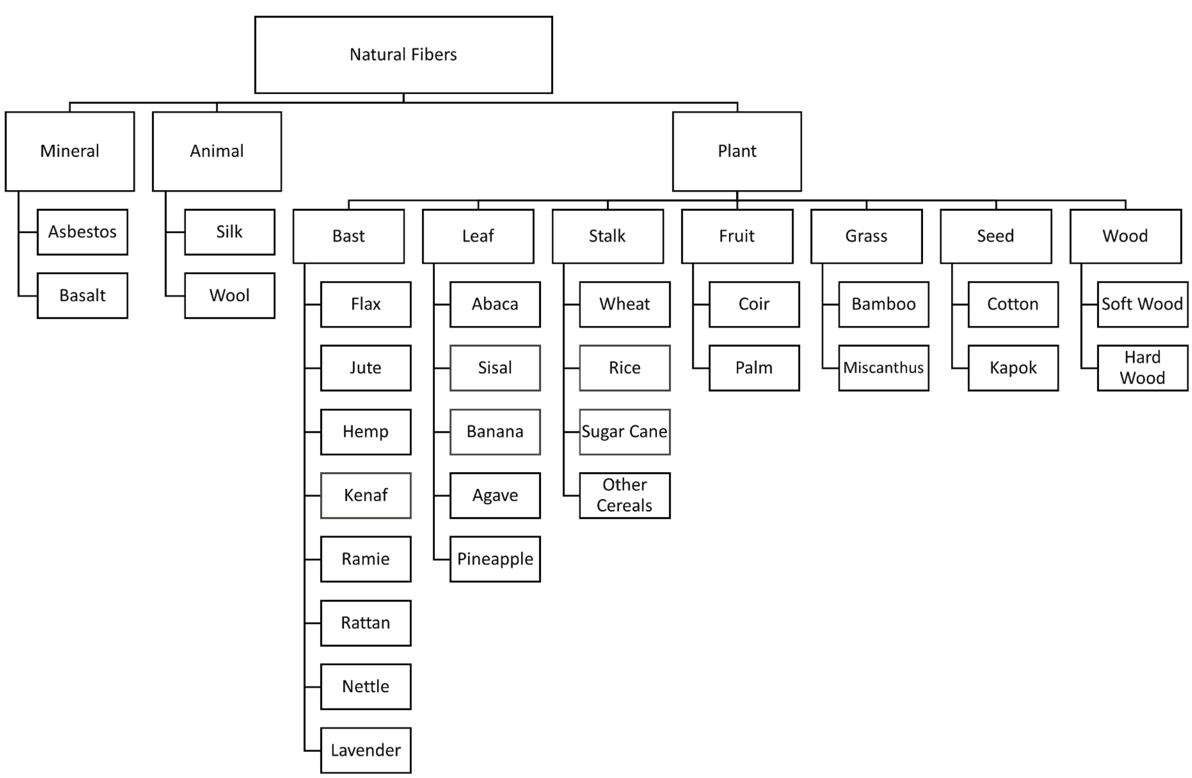

Fig. 2. Overview of Natural Fibers. Based on Gurunathan et al. (2015); Shadhin et al. (2023); Thakur et al. (2014); Zwawi (2021).

are deep, well aerated and have strong plant available water capacity, which supports stable yields under increasingly uneven rainfall (LGRB, 2025). Clay rich soils occur in several upland and foreland areas and are more compact but provide marked buffering and filtration capacity, which enhances nutrient retention and resilience to intense rainfall (LGRB, 2025). In the higher elevations of the Black Forest coarse textured and often shallow sandy soils are common, which are nutrient poor with limited water holding capacity and therefore more sensitive to drought stress (LGRB, 2025).

Against this background the selection of fiber crops follows a multi-step elimination process. First, climatic feasibility restricts the set of global fiber crops depicted in Fig. 2 to those that can be cultivated under regional conditions, which initially includes flax, hemp, miscanthus, lavender, nettle, wheat, bamboo and several woody species. Second, processing considerations exclude crops that require conversion into regenerated fibers, which removes softwood and hardwood species. Third, data availability excludes crops for which no reliable regional cultivation data exist, such as bamboo despite partial climatic suitability. From the remaining options five crops fulfil the selection criteria. The study therefore focuses on hemp, miscanthus, lavender, nettle and wheat straw, with flax serving as the benchmark due to its established role in biocomposite applications and its relevance for CFW (Dambrosio et al., 2024; Mindermann et al., 2022a, 2025).

2.2. Criteria selection

The selected fiber crops are evaluated based on their sustainability and their technical suitability, focusing on CFW applications. The criteria are derived from an extensive literature review of both biocomposite specific studies and of literature on sustainable biomass selection for industrial applications. In total, 30 studies were reviewed resulting in 31 criteria, see Appendix A. Out of the identified criteria, eight were chosen to represent the economic, environmental, social and technical dimensions as summarized in Table 1. Several initially identified criteria were excluded due to (1) insufficient empirical data for regional fiber crops, (2) redundancy, or (3) limited relevance to CFW applications. The performance of each crop across the defined criteria is assessed using a set of quantitative and qualitative metrics, see Table 1.

2.2.1. Economic criteria

The economic dimension reflects the competitiveness and supply potential of fiber crops in the regional contexts. Out of the economic criteria identified in the literature, three were selected. First, the fiber output in tons per hectare (t/ha) is calculated. It serves as a basis on which quantitative metrics can be compared across crops and reflects the land-use-efficiency regarding fiber production targets. The current supply capacity is the sum of the crop's fiber output multiplied with current (2013–2023) land allocation data for BW. The supply capacity directly determines the availability of feedstock for CFW applications ensuring that fibers are evaluated by their capacity to provide sufficient material volumes at scale. The price of biomass and fibers was selected as complementary criteria to capture the market dimension. Prices influence competitiveness, land allocation and adoption in construction applications.

2.2.2. Environmental criteria

The literature review revealed a wide range of environmental parameters used to evaluate NF, see Appendix A. However, many of these criteria are difficult to apply consistently at a regional scale, either because empirical data is scarce or because the indicators are highly context specific. For this reason, the framework focuses on two environmental criteria that are both widely referenced in the literature and feasible to assess for the selected crops.

Input intensity captures the direct environmental pressures of cultivation. Fertilizer, pesticide, and water and energy required for the cultivation directly shape the ecological profile of the fiber crops. A low input requirement is therefore regarded as environmentally more sustainable. For dual use crops, such as lavender and wheat, a weight-based input allocation is applied. The allocation is based on literature data on wheat cultivation (Borrion et al., 2012; Ingrao et al., 2018; Wang et al., 2013) and essential oil production (Aprotosoaie et al., 2017; Lesage-Meessen et al., 2018; Zheljazkov et al., 2013).

The criterion "ecosystem services" is included to reflect both positive and negative contributions of crops, such as soil fertility improvement, carbon sequestration or the negative impact of plant protection on biodiversity. While these effects are more difficult to quantify than input levels, excluding them would overlook relevant co-benefits.

Table 1
Selected sustainability and suitability criteria and metrics.

Dimension	Criteria	Description	Metric
Economic	Fiber Output	Amount of the fiber output per hectare and year as the product of biomass yield and fiber content.	■ Biomass yield ■ Fiber content
	Supply capacity	Represents the current supply potential of the fiber crops as the product of fiber output and cultivated area in BW.	■ Fiber output ■ Cultivation area
	Price	Price of fiber crop biomass and fiber products.	■ Biomass price ■ Fiber price
Environmental	Input intensity	Quantity of inputs needed for fiber crop cultivation including fertilizer, plant protection, water and energy.	■ Fertilizer input ■ Water requirement ■ Energy requirement ■ Plant protection requirement
	Ecosystem services	Comprises ecosystem services related to biodiversity impacts, regulating services and impacts on soil quality.	■ Soil impact ■ Phytoremediation capability ■ Habitat services ■ Pollinator support ■ Plant protection requirement
Social	Food security impact	Captures the competition between fiber crops and food/ feed crops for arable land.	■ Provisioning services ■ Soil requirements
Technical	Physical properties	Physical appearance of the fibers expressed by fiber length, fiber diameter, and density.	■ Fiber length ■ Fiber diameter ■ Density
	Mechanical properties	Contains tensile strength, Young's modulus, and elongation at break, which characterize the mechanical behavior of the fibers.	■ Tensile strength ■ Specific tensile strength ■ Young's modulus ■ Specific Young's modulus ■ Elongation at break

2.2.3. Social criteria

For the social dimension, food security impact was selected as the sole criterion. It reflects the competition between fiber crops and food or feed crops for arable land. Given the fiber quantities required for CFW production, potential trade-offs with food security must be considered, particularly in a region, such as BW, where agricultural land is limited.

2.2.4. Technical criteria

Successful implementation of bio-based materials in CFW depends on several key processing parameters, underscoring the complexity of implementing bio-based systems within CFW and highlight the need for an integrated approach to material selection, processing optimization, and performance evaluation.

The technical dimension reflects both the processability of individual fibers into semi-finished products and the achievable quality of the finished components. Physical properties include fiber length, diameter, and density. These parameters determine the physical appearance of the fibers and strongly influence processability. Fiber length and diameter affect bundle coherence and hairiness, which are central to performance in CFW. In general, longer fibers enhance yarn performance due to greater overlap per unit length, reducing the need for force transfer across fiber interfaces. Fiber diameter, when considered relative to length and at a constant yarn cross-section, primarily informs processability rather than mechanical performance. Density is used to calculate specific material properties as well as the achievable composite architecture. High bundle coherence enables fibers to withstand the tension, abrasion, and bending stresses during winding, but may reduce matrix impregnation. Conversely, excessive hairiness can lead to yarn breakage, contamination of the matrix, and blockages in the system, undermining processing stability and fiber volume ratio (FVR) accuracy. Consistency in these parameters is therefore essential to avoid issues such as matrix leakage or irregular winding tension.

Mechanical properties include tensile strength, Young's modulus, and elongation at break. These determine both the handling of fibers during winding and the performance of the final composite. The tensile strength characteristic value is the maximum tensile force that can be applied in relation to the initial cross-section and thus expresses the load-bearing capacity of the fibers. In turn, this defines the total amount of fiber required. For comparability between crops of different densities, specific tensile strength as the quotient of the tensile strength and the density is used. Young's modulus is the proportionality factor between the force applied to the initial area and the resulting deformation and reflects stiffness. It likewise affects the required fiber quantities and final component design, with a specific modulus calculated for consistency across crops. Elongation at break is defined as the permanent percentage change in the length of the material at the moment of failure, relative to its initial length. It describes the ability of the material to deform before failure, increasing the probability of detecting damage before collapse.

Fiber–matrix bonding is a decisive factor for the structural performance of CFW composites, but it was excluded from the criteria in this study. For the uncommon fiber crops considered here, no representative samples were available for testing, and literature data are insufficient to provide reliable values. Since bonding strongly depends on surface chemistry and processing conditions, it cannot be reasonably compared across crops at this stage.

2.3. Data

The evaluation relies on data from diverse research fields, including biodiversity studies, agronomic reports, life-cycle assessments, market analyses, and material sciences. Data collection faced two main challenges. Firstly, since the focus lies on BW, the objective was to gather region-specific cultivation data that reflect local climate and soil conditions. To supplement peer-reviewed sources, industry reports and grey literature (e.g., cooperative reports, government publications) were also included. However, data availability varies considerably between crops.

Secondly, the availability of data on fiber content, biomass and fiber prices and lastly mechanical characteristics depends on the existence of commercial fiber production. To ensure comparability of physical and mechanical properties, values were extracted from as few sources as possible. Nevertheless, differences in testing conditions, such as load case or testing speed, made it unavoidable to combine heterogeneous sources. In some instances, values were obtained indirectly, for example from composite or fiber testing. Since the study covers fiber crops with limited research coverage and no established production processes, data for all metrics could not be obtained consistently across the entire crop selection. For the fiber output criterion, uncertainty in biomass yield and fiber content data was addressed by applying a Monte Carlo simulation. The simulation is based on 10k random draws from uniform distributions defined by reported minimum and maximum values for yield and fiber content. For miscanthus and wheat straw, no crop-specific fiber content values were available in the literature. To enable their inclusion in the analysis, a range of 5–20 % was applied to reflect a low to medium fiber content (Bogard et al., 2022; Martz et al., 2024). Region-specific price data is only available for wheat straw. Price data for flax, hemp, miscanthus, and nettle is obtained from the European market. As lavender fiber production remains limited to research initiatives, no price data for lavender stems is available.

2.4. Benchmark comparison

The evaluation of alternative fiber crops in this study follows a benchmark comparison approach, with flax used as the reference material. Flax is not necessarily the optimal fiber across all sustainability dimensions, but its widespread use, especially in CFW, and established supply chain in Europe make it a suitable baseline for assessing alternatives. The study applies a relative comparison rather than an absolute ranking. Each fiber crop is assessed against flax across the selected sustainability and suitability criteria, highlighting areas where alternatives demonstrate superior, comparable, or inferior performance. A relative ranking is derived from these individual comparisons to identify crops with the highest potential as alternatives to flax. The four dimensions, economic, environmental, social, and technical, are considered equally, with no weighting applied, to ensure a balanced assessment. Crops that perform positively across all criteria are considered more suitable than those that excel in only one dimension, reflecting the value of consistent, well-rounded performance.

3. Results and discussion

3.1. Economic sustainability

The economic analysis evaluates the fiber output per hectare as well as the overall supply capacity in BW considering land allocation and price dynamics. Table 2 shows the annual fiber output as the product of biomass yield and fiber content, referring to the amount of raw, unprocessed fibers that can be obtained per hectare. The crops can be grouped into those with higher fiber output compared to the benchmark, and those with lower output. Considering mean values, miscanthus and particularly hemp outperform flax with respectively more than double (2x) and triple (3x) its fiber output. Lavender, nettle and wheat straw show a lower mean output, although nettle and wheat are close to the 1.1 t/ha benchmark of flax. Taking the minimum and maximum values into consideration, the high land-use efficiency of hemp becomes even more apparent, while nettle shows the potential of a higher fiber output than flax.

When current land allocation is taken into account, the ranking shifts considerably. Wheat straw is the most abundant fiber source, with an estimated mean annual output of approx. 192k t/a. This outcome is primarily the result of the extensive wheat cultivation in BW (Statistisches Landesamt BW, 2024). Hemp and miscanthus follow at a significantly lower supply capacity, with mean annual outputs of 1511 t and 914 t respectively. Despite its competitive per hectare output, there is no reported cultivation (See n.d. in Table 2) of flax in BW and therefore no statement on the regional supply capacity can be made. The annual outputs of nettle and lavender remain negligible under present conditions. These findings highlight the importance of distinguishing between land-use efficiency in terms of fiber output per hectare and fiber supply based on the allocated land. The latter being determined by land allocation decisions, which are influenced by market dynamics such as demand and price fluctuations. Fig. 3 establishes a price hierarchy for the different fiber crops, enabling an assessment of their attractiveness

Table 2
Literature data and calculations on biomass availability of fiber crops in BW.

Metric		Flax	Main Ref.	Hemp	Main Ref.	Miscanthus	Main Ref.	Lavender	Main Ref.	Nettle	Main Ref.	Wheat Straw	Main Ref.
Yield	min.	2.6	Agrargenossenschaft BC (2014); Coon et al. (2014); FNR (2008)	10.0	Grégoire et al. (2021)	10.0	Lewandowski et al. (2000); Moll et al. (2020)	0.5	Demir et al. (2022); Flanagan (2020)	0.4	Bogard et al. (2022); Vogl and Hartl (2003)	5.9	KTBL (2024a, 2024b)
[t/ha]	mean	4.3		12.5		20.0		2.0		5.7		6.9	
	max.	6.0		15.0		30.0		3.4		11.0		7.9	
Fiber	min.	18.0	Gomez-Campos et al. (2021); Grégoire et al. (2021)	28.0	FNR (2008)	5.0	Bogard et al. (2022); Martz et al. (2024)	5.0	Biopro (2023)	6.0	Bogard et al. (2022); Schneider and Beckhaus (2020)	5.0	Bogard et al. (2022); Martz et al. (2024)
Content	mean	25.4		28.0		12.5		7.5		14.1		12.6	
[%]	max.	33.0		28.0		20.0		10.0		22.0		20.0	
Fiber	min.	0.5	*calculated*	2.8	*calculated*	0.5	*calculated*	0.0	*calculated*	0.0	*calculated*	0.3	*calculated*
Output	mean	1.1		3.5		2.5		0.2		0.8		0.9	
[t/ha]	max.	2.0		4.2		6.0		0.3		2.4		1.6	
Cultivation Area [ha]		n.d.		432	BLE (2021)	366	Ministerium für Ernährung (2013)	1.8	Biopro (2023)	n.d.		222,000	Statistisches Landesamt Baden-Württemberg(2024)
Supply	min.	n.d.	*calculated*	1209	*calculated*	198	*calculated*	0.1	*calculated*	n.d.	*calculated*	67,333	*calculated*
Capacity	mean	n.d.		1511		913		0.3		n.d.		192,079	
[t/a]	max.	n.d.		1814		2180		0.6		n.d.		348,988	

to both producers and consumers, in this case, farmers and manufacturers of NF biocomposites. The hierarchy is derived from observed market prices of biomass crops over the past decade, adjusted for inflation with 2020 serving as the base year (Eurostat, 2022). This standardization enables consistent comparison of biomass and fiber prices across different years.

The price distribution shows clear differences between crops. Biomass prices have fluctuated strongly over the past decade due to changing demand and weather-related yield shocks (Alliance for European Flax-Linen and Hemp, 2024). Flax in particular shows volatility with a coefficient of variation (CV) of 0.73. The CV measures the relative variability of a dataset by expressing the standard deviation as a proportion of the mean. Hemp, by contrast, has maintained more stable prices, with a median price above flax and a CV of 0.16. For producers, this stability makes hemp an attractive crop choice compared to flax. Miscanthus biomass and wheat straw are priced significantly lower, reflecting their predominant use in low-value applications such as bioenergy (Witzel and Finger, 2016). With a CV of 0.62, both crops show a better price stability than flax. In the case of wheat straw, low prices are feasible since straw is a byproduct of more profitable grain production. Reliable data for nettle prices is scarce, but available values suggest prices around 1.6 x higher than flax and a CV of 0.67. This wide range may not reflect market dynamics, as in the case of flax, but rather the very limited number of observations (Viotti et al., 2022). Higher nettle prices could create opportunities for small-scale suppliers, though limited cultivation experience and more complex agricultural practices persist (Institut für Pflanzenkultur e.K., 2019). Lavender faces similar challenges, intensified by uncertainties in processing and market development.

However, for CFW applications fiber prices, not biomass prices, determine economic viability. There is no established market for fiber products from miscanthus, lavender, nettle, or wheat straw. The assessment of these crops is hence limited to biomass prices. In contrast, flax and hemp fibers are already available on the market, allowing direct comparison. Fig. 2 shows that flax fibers average about 2.8 €/kg, roughly twice the median hemp fiber price. Yet this gap is overstated, as CFW applications primarily use lower-grade flax fibers (Graupner et al., 2020).

3.2. *Environmental sustainability*

Fig. 4 illustrates the differences in input requirements per ton of fiber output across the examined crops. Hemp exhibits lower fertilizer needs than flax, except in the case of potassium, whereas most other alternative fiber crops generally require higher levels of input. This can be attributed to two different reasons: While lavender requires significantly less fertilizer than flax, its fiber output per hectare is around 80 % lower than that of flax, resulting in a high relative requirement. Wheat straw and nettle, in contrast, have a considerably higher absolute fertilizer demand leading to a weaker performance despite their medium to high fiber output. Miscanthus presents a more nuanced case as nitrogen and phosphorous demands are lower than those of flax, while its potassium and lime demand exceed the benchmark.

A similar pattern can be observed when energy and water requirements are compared. Hemp remains the best performing crop followed by miscanthus, while lavender and wheat straw are above the benchmark of 3200 MJ/t and 340mm/t, indicating an inferior performance. There is no available data on the energy or water requirements of nettle. Since the crop is generally regarded as water-loving and associated with moist habitats such as riversides (Viotti et al., 2022; Vogl and Hartl, 2003), a relatively high water demand may be assumed. However, the water requirements of all selected crops are currently covered by rainfall in BW. Considering the increasing frequency of extreme weather events such as droughts (Imbery et al., 2024), this criterion can be considered primarily forward-looking.

Plant protection requirements can be taken into account for the input

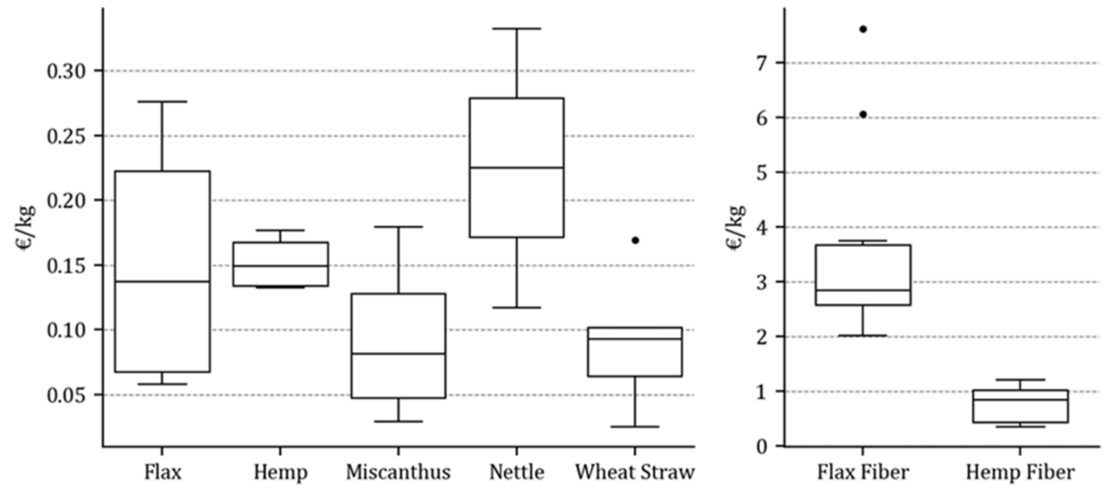

Fig. 3. Biomass (left) and fiber prices (right), presented in real terms with 2020 as the base year. See Appendix B for references.

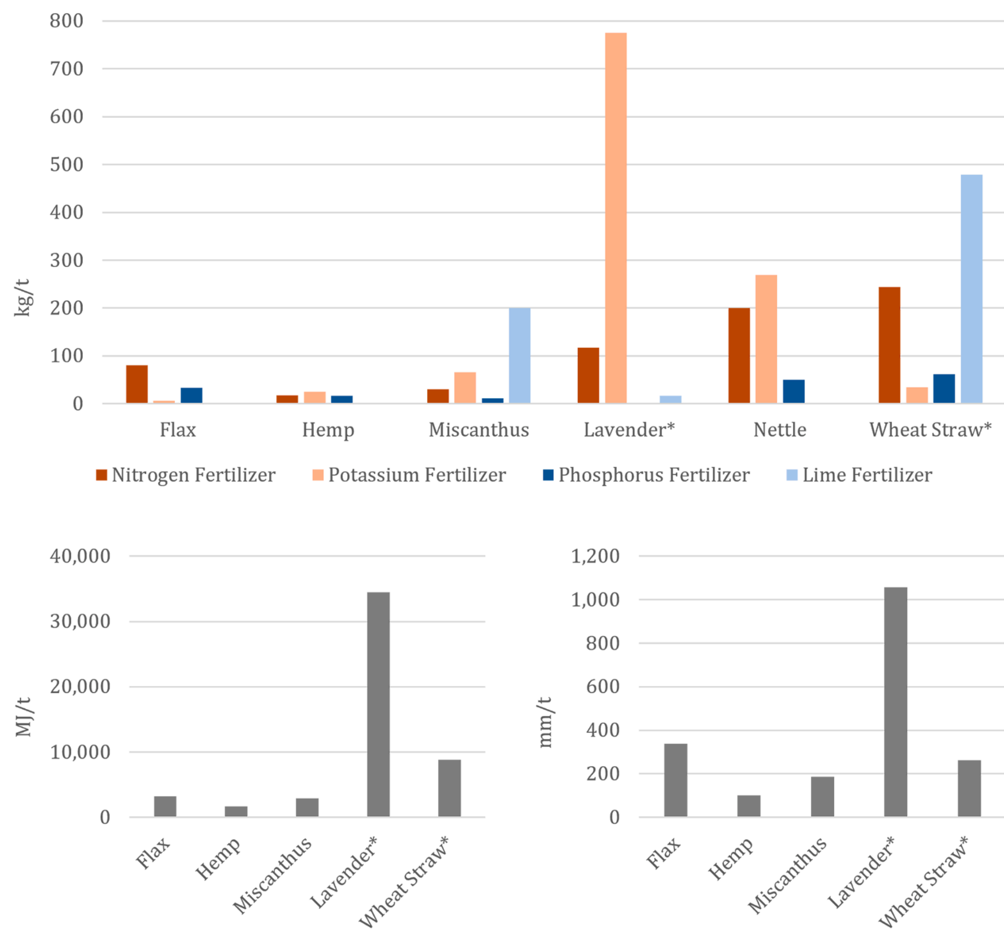

Fig. 4. Fertilizer (top), energy (bottom-left) and water requirement (bottom-right) per ton of fiber output per crop. *weight-based allocation based on the residue weight compared to the full plant. (See 2.2.2. for details). See appendix B for references.

intensity criteria as well as for their impact on the surrounding ecosystem. The literature findings in Table 3 emphasize hemp, as the only fiber crop not requiring plant protection measures as its fast growth suppresses weeds. Miscanthus, Lavender and Nettle share similar requirements: Mechanical or chemical weed control can be necessary in the establishment phase but can be considered low. Flax and particularly wheat require chemical weed control due to the open crop structure.

Regarding ecosystem services, hemp stands out for its positive impacts such as soil erosion prevention, high carbon sequestration, phytoremediation capabilities as well as habitat services and particularly pollinator support due to late flowering (European Environment Agency, 2007; FNR 2008). These consistently positive characteristics also largely apply to nettle and miscanthus (Sa et al., 2020; Viotti et al., 2022). Literature data on lavender ecosystem services is limited to reports of positive habitat services and pollinator support (Kozuharova and Vereecken, 2024). Wheat performs least favorably, with high

Table 3
Overview of literature results on ecosystem services of fiber crops.

Metric	Flax	References	Hemp	References	Miscanthus	References	Lavender	References	Nettle	References	Wheat Straw	References
Soil Impact	Alleviates soil compaction; Prevents soil erosion; High carbon sequestration	CELC (2022); FNR (2008); Turunen and Van Der Werf (2007)	Deep roots prevent soil compaction and erosion; High carbon sequestration	Adesina et al. (2020); Biswakarma et al. (2023); Cherney and Small (2016); FNR (2008); Kaur and Kander (2023)	High biomass accumulation improves soil quality; Prevents soil erosion	European Environment Agency (2007); Lewandowski et al. (2000); McCalmont et al. (2017); Tsalagkas et al. (2021)	n.d.		High biomass accumulation improves soil quality	Viotti et al. (2022)	Intensive rooting alleviates soil compaction; Limited soil erosion prevention	European Environment Agency (2007); Sun et al. (2020)
Phytoremediation Capability	n.d.		Remediation of heavy-metal polluted soil	Biswakarma et al. (2023); Cherney and Small (2016); Kaur and Kander 2023; Meffo Kemda et al. (2024)	Remediation of heavy-metal polluted soil	Sa et al. (2020)	n.d.		Remediation of nitrate and phosphate overloaded soils	Viotti et al. (2022)	n.d.	
Habitat Services	Open crop structure allows weed growth as fodder	European Environment Agency (2007)	Provides shelter	European Environment Agency (2007); Meffo Kemda et al. (2024)	Provides shelter and fodder during winter	Lewandowski et al. (2016); McCalmont et al. (2017); Sa et al. (2020)	Promotes high species richness	Kozuharova and Vereecken (2024)	Promotes biodiversity of local flora and fauna	FNR (2024); Viotti et al. (2022); Vogl and Hartl (2003)	Direct impacts of plant protection requirement on habitat quality	European Environment Agency (2007); Halpern et al. (2022)
Pollinator Support	n.d.		Late flowering supports pollinators	Adesina et al. (2020); European Environment Agency (2007); Kaur and Kander (2023); Meffo Kemda et al. (2024)	Little to no impact on pollinators	European Environment Agency (2007); Lewandowski et al. (2016); Sa et al. (2020)	Promotes high species richness especially in bees	Kozuharova and Vereecken (2024)	Host plant of several butterfly species	FNR (2024); Viotti et al. (2022); Vogl and Hartl (2003)	Dense cover suppresses weeds	European Environment Agency (2007)
Plant Protection Requirement	Requires chemical plant protection measures	CELC (2022); FNR (2008); Gomez-Campos et al. (2021); Röhricht (1998); Stavropoulos et al. (2023); Turunen and Van Der Werf (2007)	Fast growth suppresses weed thus no plant protection necessary	Barth (2015); FNR (2008); Kaur and Kander (2023); Scalabrin et al. (2024)	Chemical plant protection measures can be necessary in the first few years	European Environment Agency (2007); KTBL (2024c); McCalmont et al. (2017)	Chemical plant protection measures can be necessary	Bashyal (2024); Flanagan (2020)	Requires mechanical weed removal in the first year	Sadik (2019)	Requires extensive chemical and mechanical plant protection measures	European Environment Agency (2007); KTBL (2024b 2024a); Meisterling et al. (2009)

fertilizer and pesticide demands lowering habitat quality and a dense canopy reducing nesting opportunities (European Environment Agency, 2007; Halpern et al., 2022).

3.3. Social sustainability

The large-scale cultivation of NF crops has social implications beyond direct economic aspects. In particular, the link between fiber crop production and food security deserves closer attention, given resource constraints and land-use competition. A main distinction can be made between crops that directly compete with food production and those that can grow on marginal land.

Flax and hemp are often incorporated in conventional crop rotations (Adesina et al., 2020; CELC, 2022), reducing direct competition for land. However, when cultivated at larger scales, both may still pose trade-offs with food production. In this context, hemp offers a comparative advantage due to its higher raw fiber yield per hectare, which translates into more efficient land use. Hemp as well as miscanthus can moreover be cultivated on marginal land (Sa et al., 2020; Scalabrin et al., 2024), further alleviating pressure on arable land. Miscanthus' perennial growth cycle and long establishment phase may however reduce flexibility in short-term land allocation. Other crops such as lavender and nettle also tolerate lower soil fertility (Viotti et al., 2022), potentially minimizing land competition with food crops, although lavender's relatively low yield and fiber content limit its efficiency. Wheat straw stands out as a byproduct of grain production and thus does not require dedicated land, making it the least likely to affect food security negatively.

3.4. Technical performance

While economic, environmental and social aspects are important in evaluating NF crops, the potential of fibers for CFW ultimately depends on their suitability for processing into semi-finished products and their technical performance. Table 4 summarizes the physical and mechanical properties. Products from flax and hemp are commercially available and can be tested directly, while data for the other fibers must be estimated based on reported physical and mechanical properties from sources around the world. These values depend on many factors, including climate, cultivation, harvest, and processing (Fuchs and Albrecht, 2012). The following statements therefore reflect a qualitative comparison of individual fiber properties. Composite properties depend on yarn production and winding and may differ from the order presented here.

This comparison does not replace real-world testing but provides an overview of available data. The decisive criterion for yarn production is fiber length, as it determines friction transfer between fibers. Lavender shows the longest fibers ranging from over 50 mm to 300 mm (Eyupoglu and Merdan, 2021; Stegmaier et al., 2024), exceeding flax (Charlet et al., 2010). Nettle (Bacci et al., 2009) and hemp (Charlet et al., 2010) are in the same range as flax, while wheat straw (Kasmani and Samariha, 2011; Pan et al., 2009) and miscanthus (Bourmaud and Pimbert, 2008; Lundquist et al., 2004), with fibers in the low millimeter range, are too short for further processing. Fiber diameter is also important, since larger diameters increase bending stiffness, making fibers harder to process, and are more prone to defects. At 295 μm (Eyupoglu and Merdan, 2021), lavender fibers are far thicker than flax (Bodros and Baley, 2008; Charlet et al., 2010; Zwawi, 2021), which complicates spinning. Extraction methods such as bacterial, enzymatic, and alkaline treatments, as well as combinations of these methods, are being investigated (Stegmaier et al., 2024), and blended yarns with fineness between 12 and 20 dtex already exist (Sarsour et al., 2023). These methods reduce diameter but also shorten fibers. Miscanthus fibers (Bourmaud and Pimbert, 2008; Lundquist et al., 2004) also exceed the flax reference (Bodros and Baley, 2008; Charlet et al., 2010; Zwawi, 2021), while hemp (Bodros and Baley, 2008; Charlet et al., 2010), nettle (Bacci et al., 2009; Bodros and Baley, 2008; Zwawi, 2021), and wheat straw (Kasmani and Samariha, 2011) are similar. Density is approximately 1.5 g/cm³ for flax (Bodros and Baley, 2008; Zwawi, 2021), hemp flax (Bodros and Baley, 2008; Zwawi, 2021), miscanthus (Lundquist et al., 2004), and nettle (Zwawi, 2021). Lavender has a lower density of 0.87 g/cm³ (Eyupoglu and Merdan, 2021). No value was found for wheat straw. The tensile strength of hemp (Bodros and Baley, 2008; Charlet et al., 2010; Zwawi, 2021) and nettle (Bodros and Baley, 2008; Zwawi, 2021) falls within the range of flax (Bodros and Baley, 2008; Charlet et al., 2010; Zwawi, 2021), with nettle at the upper end and hemp at the lower end. Lavender (Eyupoglu and Merdan, 2021) has lower tensile strength than flax (Bodros and Baley, 2008; Charlet et al., 2010; Zwawi, 2021) and miscanthus (Lundquist et al., 2004), but it has higher tensile strength than wheat straw (Pan et al., 2009). In terms of Young's modulus (Bodros and Baley, 2008; Charlet et al., 2010; Eyupoglu and Merdan, 2021; Lundquist et al., 2004; Pan et al., 2009), the classification of the fibers corresponds to their tensile strength classification. Considering density, lavender performs slightly better in specific tensile strength and specific Young's modulus due to its lower density, while the others show little difference.

3.5. Ranking of flax alternatives

Flax serves as the benchmark fiber in this assessment. However, its established position reflects not only its agronomic and technical attributes but also the cumulative effects of long-term optimization and infrastructure development. This historical advantage may distort perceptions of its relative competitiveness, especially when compared to less established alternatives that have not yet benefited from similar levels of investment or adaptation. Nevertheless, the assessment shows that flax performs well in both sustainability and technical criteria. From a land-use efficiency perspective, its lower yield and the absence of current cultivation in BW limit the available fiber supply. The economic assessment further identifies considerable price volatility, which may constrain the potential for future expansion. In this context, the results provide the basis for a comparative ranking of flax fiber alternatives. While each crop demonstrates context-specific advantages and trade-offs, the data indicate a clear pattern in relative performance across the evaluated dimensions.

Hemp is the highest-performing alternative to flax. In addition to its low input requirements, hemp contributes positively to ecosystem functions, including pollinator support and soil enhancement. Its limited reliance on plant protection measures offers a particular advantage over flax. From an economic perspective, hemp demonstrates strong potential, with a mean fiber output approximately three times greater than that of flax. Furthermore, stable market prices and continued efforts to expand regional cultivation (BLE, 2021; MLE, 2024) indicate that hemp production is likely to grow in the coming years. If this expansion is directed toward marginal land rather than displacing food or feed crops, the risk of negative impacts on food security can be minimized. Lastly, the physical properties allow further processing, with performance somewhat lower than flax but still technically sound. The tensile strength and Young's modulus ranges for flax and hemp overlap, but flax's average values are higher in both cases. Experiments have already proven that, at the material level, flax has higher strength and stiffness (Mindermann et al., 2022a). Similar to flax, semi-finished products are available, and initial applications have been reported.

Nettle represents another viable alternative to flax, as it performs well across the range of criteria. Its favorable mechanical characteristics, including fiber strength and spinnability, support its suitability for fiber applications and imply a performance comparable to that of flax. Although large-scale cultivation is not currently practiced, its high biomass and fiber content still suggest potential as a fiber crop. From an environmental and social perspective, nettle offers advantages such as the ability to grow on degraded land and its preference for moist soils, which could support cultivation on marginal sites and reduce

Table 4
Physical and mechanical properties.

Metric	Flax	Main Ref.	Hemp	Main Ref.	Miscanthus	Main Ref.	Lavender	Main Ref.	Nettle	Main Ref.	Wheat Straw	Main Ref.
Fiber length [mm]	4–80	Charlet et al. (2010)	5–55	Charlet et al. (2010)	0.5–1.2	Bourmaud and Pimbert (2008); Lundquist et al. (2004)	> 50–300	Eyupoglu and Merdan (2021); Stegmaier et al. (2024)	43–58	Bacci et al. (2009)	0.3–1.1	Kasmani and Samariha (2011); Pan et al. (2009)
Fiber diameter [µm]	5–76	Charlet et al. (2010); Zwawi (2021)	10–51	Charlet et al. (2010)	13–230	Bourmaud and Pimbert (2008); Lundquist et al. (2004)	295	Eyupoglu and Merdan (2021)	19–80	Bacci et al. (2009); Zwawi (2021)	19	Kasmani and Samariha (2011)
Density [g/cm^3]	1.5–1.53	Bodros and Baley (2008); Zwawi (2021)	1.48	Bodros and Baley (2008); Zwawi (2021)	1.53–1.54	Lundquist et al. (2004)	0.87	Eyupoglu and Merdan (2021)	1.51	Zwawi (2021)	n.d.	
Tensile strength [MPa]	345–2000	Charlet et al. (2010); Zwawi (2021)	270–1100	Bodros and Baley (2008); Charlet et al. (2010)	743–913	Lundquist et al. (2004)	227	Eyupoglu and Merdan (2021)	650–1594	Bodros and Baley (2008); Zwawi (2021)	43	Pan et al. (2009)
Specific tensile strength [MPa*cm^3/g]	225–1333	*calculated*	182–743	*calculated*	482–597	*calculated*	261	*calculated*	430–1056	*calculated*	n.d.	
Young's modulus [GPa]	30–110	Charlet et al. (2010)	19–70	Bodros and Baley (2008); Charlet et al. (2010)	60	Lundquist et al. (2004)	5–8	Eyupoglu and Merdan (2021)	87	Bodros and Baley (2008)	3	Pan et al. (2009)
Specific Young's modulus [GPa*cm^3/g]	20–73	*calculated*	13–47	*calculated*	39	*calculated*	6–9	*calculated*	58	*calculated*	n.d.	
Elongation at break [%]	1.2–3.3	Bodros and Baley (2008); Charlet et al. (2010)	0.8–1.8	Bodros and Baley (2008); Charlet et al. (2010)	0.8–2	Bourmaud and Pimbert (2008)	1.1–4.7	Eyupoglu and Merdan (2021); Stegmaier et al. (2024)	1.7–2.6	Bodros and Baley (2008); Zwawi (2021)	3.8	Pan et al. (2009)

Note: This table contains values for elementary fibers and fiber bundles.

competition with conventional crops. However, its specific growing requirements and the lack of standardized cultivation practices may limit its feasibility for commercial production. Moreover, its historical decline and repeated, unsuccessful attempts to re-establish cultivation (Schneider and Beckhaus, 2020) suggest that a significant expansion of nettle cultivation in BW is unlikely. Yet, from a mechanical standpoint, nettle fibers are the most interesting alternative to flax in this selection. Fiber length and diameter indicate that nettle can be processed similar to flax without the need of adapted technology. The tensile strength and Young's modulus are comparable to those of flax, which is why sufficient mechanical potential for CFW applications can be assumed.

Lavender is a largely unexplored fiber crop. It is well adapted to dry conditions and requires relatively low input. However, its low biomass yield, limited fiber content, and the absence of regional cultivation result in an annual fiber supply capacity of less than 1 t. Combining fiber provision with the economically viable production of essential oils may offer a complementary use case in regions of traditional lavender cultivation, but its overall contribution to regional fiber supply is expected to remain limited. From a process engineering perspective, it is primarily the large diameter of the fibers compared to flax that would make processing difficult, but this could be overcome by alternative fiber extraction processes. Blended yarns with fineness between 12 and 20 dtex already exist. Since the density of lavender is nearly half that of the other fibers in this selection, its specific tensile strength and specific Young's modulus improve in comparison. Lavender's specific tensile strength values reach the lower range of flax, but its specific Young's modulus remains below the range of flax. Nevertheless, lavender remains of interest as a potential fiber crop for CFW applications.

The technical performance assessment highlights the importance of fiber length for spinnable fiber products, which excludes **miscanthus** and **wheat straw** as suitable fiber suppliers for CFW applications. Nonetheless, their potential for use in composite technologies remains a point of interest e.g., as fillers in the form of particles. Wheat straw appears particularly promising due to its widespread availability in BW. As a byproduct of wheat cultivation, its use does not require additional land resources, thereby reducing potential conflicts with food production. Similarly, the high biomass yield of miscanthus suggests a land-efficient fiber supply. However, further research into processing technologies for both wheat straw and miscanthus is necessary to clarify their potential as fiber sources in the regional context. Alternative options for producing textile semi-finished materials for CFW when individual fibers are too short for classical spinning (e.g., miscanthus, wheat) include:

- Partially breaking down plant material, as opposed to completely breaking it down to elementary fibers, and spinning agglomerates of elementary fibers using conventional spinning processes.
- Using a sliver, a fluffy fiber band that is an intermediate product of the yarn production process. Slivers have been successfully used in CFW (Mindermann et al., 2022b). Processing slivers requires higher linear density to ensure sufficient bundle coherence, reducing the number of layers and interlocking and thus usually leading to a lower FVR and reduced mechanical properties. Slivers processed so far with CFW have been crocheted to increase bundle coherence, although processing slivers without such measures may also be possible.
- Layering mesoscopic fiber strips (Doubling) taken from the plant without breakdown. For instance, bast strips from hemp have been layered with overlaps to form a fibrous material for CFW, requiring additional measures to enhance bundle coherence. Initial tests with such fiber semi-finished products using CFW confirm their sufficient processability.
- Combining individual fibers into a tape with a binder material, often thermoplastic. Flax tape, successfully used in CFW, exemplifies this process (Mindermann et al., 2022b). The additional binder reduces the matrix content of the thermoset matrix but improves behavior during impregnation and layering compared to highly twisted yarns, owing to a better surface-to-volume ratio.
- Producing a wet-laid nonwoven and cutting it into a continuous strip, which could be used as fibrous material for CFW processing. However, there is currently no experience with this approach, and nonwoven materials are expected to have lower material properties, but better impregnation characteristics compared to yarns.

The bundle cohesion of the textile semi-finished products mentioned above can be insufficient and therefore enhanced through additional intermediate processes such as crocheting, wrapping, or braiding utilizing another secondary fiber material. Secondary fiber materials often include yarns made of polyester or cotton, affecting the sustainability of the material.

4. Conclusion

This study offers a comprehensive assessment of regional fiber crops in BW, Germany and examines their potential as sustainable fiber sources for bio-based composite materials, with a particular focus on the application in CFW. Hemp, miscanthus, lavender, nettle and wheat straw were evaluated and benchmarked against flax using economic, environmental, social and technical performance criteria. The results identify hemp as the most viable and readily available alternative to flax for CFW applications, due to its favorable environmental profile, high fiber yield and promising market prospects. Nettle and lavender show more limited, context-specific potential, yet they remain attractive and sustainable options for practitioners when capacity for spinning trials is available. Wheat straw and miscanthus are not suitable for direct use in CFW because their fiber length is insufficient. These fibers require additional fundamental research on extraction methods. Given their considerable availability, research that aims to generate high quality yarns would be particularly valuable. Translating these findings into practical outcomes requires addressing critical gaps in both cultivation and processing. The potential of these crops as sustainable fiber suppliers can only be realized through targeted efforts that build a resilient and regional fiber value chain. Two areas of action are particularly important:

(1) Expanding hemp cultivation could significantly improve fiber availability while maintaining land-use efficiency and economic viability. Strengthening the regional cultivation and processing capacity, by supporting local fiber processing facilities, would reduce dependence on external supply chains and support local economic development. In addition, providing farmers with guidance and training on cultivation, harvesting, and post-harvest processing, alongside clear rules on THC levels, certification, and market access, would lower barriers for first-time growers and encourage longer-term investment.

(2) Beyond hemp, exploring the role of alternative fiber sources such as wheat straw may contribute to a more diversified and stable raw material base for bio-based composites. As a widely available byproduct, wheat straw can serve as a supplementary fiber input, expanding the biobased resource supply. Further research on spinnability and fiber processing methods is essential to determine its technical suitability. On the supply side, providing information on quality demands, logistics, and market opportunities could facilitate greater residue valorization and unlock broader material options for bio-based construction, ultimately contributing to a more diversified and resilient bioeconomy.

CRediT authorship contribution statement

Alina J. Rossa: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Daniel Christopher Bozó: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Pascal Mindermann:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis. **Götz T. Gresser:** Validation. **Franziska Schuenemann:** Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Alina J. Rossa reports financial support was provided by State of Baden-Wurttemberg Ministry of Food Rural Areas and Consumer Protection. Daniel Christopher Bozo reports financial support was provided by State of Baden-Wurttemberg Ministry of Food Rural Areas and Consumer Protection. Pascal Mindermann reports financial support was provided by State of Baden-Wurttemberg Ministry of Food Rural Areas and Consumer Protection. Daniel Christopher Bozo reports financial support was provided by German Research Foundation. Pascal Mindermann reports financial support was provided by German Research Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank Stephan Baz for discussing the fiber spinning aspects of the study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.clcb.2025.100199.

Data availability

Data will be made available on request.

References

Adesina, I., Bhowmik, A., Sharma, H., Shahbazi, A., 2020. A review on the current State of knowledge of growing conditions, agronomic soil health practices and utilities of hemp in the United States. Agriculture 10, 129. https://doi.org/10.3390/agriculture10040129.
Agrargenossenschaft, B.C., 2014. Agrargenossenschaft „Bergland" Clausnitz e.G.: anbauerfahrungen Öllein [WWW Document]. URL. http://www.rekulta.org/fileadmin/downloads/PROJEKT_NAWARO/%C3%96llein-Fachveranstaltung/03_2014_01_28_Ehrler_Praktikerbericht_Anbauerfahrungen.pdf (accessed 4.5.24).
Ahmad, F., Choi, Hyun Seok, Choi, Heung Soap, Choi, Heung Soap, Park, Myung Kyun, Park, M.K., 2015. A review: natural Fiber composites selection in view of mechanical, light weight, and economic properties. Macromol. Mater. Eng. 300, 10–24. https://doi.org/10.1002/mame.201400089.
Alliance for European Flax-Linen & Hemp, 2024. Focus on the economic situation of European flax-linen and hemp [WWW Document]. URL. https://allianceflaxlinenhemp.eu/en/flax-linen-hemp-economic-observatory (accessed 4.5.24).
Aprotosoaie, A.C., Gille, E., Trifan, A., Luca, S.V., Miron, A., 2017. Essential oils of Lavandula genus: a systematic review of their chemistry. Phytochem. Rev. 16, 1–39. https://doi.org/10.1007/s11101-017-9517-1.
Bacci, L., Baronti, S., Predieri, S., Di Virgilio, N., 2009. Fiber yield and quality of fiber nettle (Urtica dioica L.) cultivated in Italy. Ind. Crops Prod. 29, 480–484. https://doi.org/10.1016/j.indcrop.2008.09.005.
Barth, M., 2015. Carbon footprint and sustainability of different natural fibres for biocomposites and insulation material.
Bashyal, J., 2024. Lavender (Lavandula angustifolia): a complete guide [WWW Document]. URL. https://scienceinfo.com/lavender-lavandula-angustifolia-a-complete-guide/ (accessed 11.14.24).
Becker, R., Schauberger, B., Merz, R., Schulz, S., Gornott, C., 2025. The vulnerability of winter wheat in Germany to air temperature, precipitation or compound extremes is shaped by soil-climate zones. Agricultural and Forest Meteorology 361, 110322. https://doi.org/10.1016/j.agrformet.2024.110322.
BIOCOM, 2022. Weizenstroh in Textilfasern verwandeln [WWW Document]. URL https://biooekonomie.de/nachrichten/neues-aus-der-biooekonomie/weizenstroh-textilfasern-verwandeln (accessed 11.15.24).
Biopro, 2023. Schwäbischer Lavendelanbau: ästhetisch und nachhaltig [WWW Document]. URL. https://www.biooekonomie-bw.de/fachbeitrag/aktuell/schwaebischer-lavendelanbau-aesthetisch-und-nachhaltig (accessed 10.23.24).
Biswakarma, N., Tripathi, K., Arya, S., Harshang, T., 2023. Industrial hemp in India: a booming botanical wonder with endless potentials.
Bundesanstalt für Landwirtschaft und Ernährung, 2021. BLE - Pressemitteilungen - Nutzhanfanbau 2021: anzahl der Betriebe und Fläche weiter gewachsen [WWW Document] URL https://www.ble.de/SharedDocs/Pressemitteilungen/DE/2021/211001_Nutzhanfanbau.html.
Bundesministerium für Ernährung und Landwirtschaft, 2023. Höherer THC-Grenzwert für Nutzhanf [WWW Document]. BMEL. URL https://www.bmel.de/SharedDocs/Pressemitteilungen/DE/2023/018-nutzhanf.html (accessed 7.2.24).
Bodros, E., Baley, C., 2008. Study of the tensile properties of stinging nettle fibres (Urtica dioica). Mater. Lett. 62, 2143–2145. https://doi.org/10.1016/j.matlet.2007.11.034.
Bogard, F., Bach, T., Abbes, B., Bliard, C., Maalouf, C., Bogard, V., Beaumont, F., Polidori, G., 2022. A comparative review of Nettle and Ramie fiber and their use in biocomposites, particularly with a PLA matrix. J. Nat. Fibers 19, 8205–8229. https://doi.org/10.1080/15440478.2021.1961341.
Borrion, A.L., McManus, M.C., Hammond, G.P., 2012. Environmental life cycle assessment of bioethanol production from wheat straw. BioMass BioEnergy 47, 9–19. https://doi.org/10.1016/j.biombioe.2012.10.017.
Bourmaud, A., Pimbert, S., 2008. Investigations on mechanical properties of poly (propylene) and poly(lactic acid) reinforced by miscanthus fibers. Compos. Part Appl. Sci. Manuf. 39, 1444–1454. https://doi.org/10.1016/j.compositesa.2008.05.023.
Carosella, S., Hügle, S., Helber, F., Middendorf, P., 2024. A short review on recent advances in automated fiber placement and filament winding technologies. Compos. Part B Eng. 287, 111843. https://doi.org/10.1016/j.compositesb.2024.111843.
European Confederation for Flax and Hemp, 2024. Economic situation of the European flax and Hemp market [WWW Document]. URL. https://allianceflaxlinenhemp.eu/en/flax-linen-hemp-economic-observatory.
Chang, Boon Peng, Chang, B.P., Mohanty, Amar K., Mohanty, Amar K., Mohanty, Amar K., Mohanty, Ajit Kumar, Misra, Manjusri, Misra, M., 2020. Studies on durability of sustainable biobased composites: a review. RSC. Adv. 10, 17955–17999. https://doi.org/10.1039/c9ra09554c.
Charlet, K., Jernot, J.-P., Breard, J., Gomina, M., 2010. Scattering of morphological and mechanical properties of flax fibres. Ind. Crops Prod. 32, 220–224. https://doi.org/10.1016/j.indcrop.2010.04.015.
Cherney, J., Small, E., 2016. Industrial hemp in North America: production. Politics and Potential. Agronomy 6, 58. https://doi.org/10.3390/agronomy6040058.
Coon, R.C., Hodur, N.M., Bangsund, D.A., 2014. Potential availability and cost of flax straw for commercial applications.
Curtis, B.C., Rajaram, S., Gómez Macpherson, H. (Eds.), 2002. Bread wheat: improvement and production, FAO plant production and protection series. Food and Agriculture Organization of the United Nations, Rome.
Dambrosio, N., Zechmeister, C., Pérez, M.G., Dörstelmann, M., Stark, T., Rinderspacher, K., Knippers, J., Menges, A., 2024. Livmats Pavilion: design and development of a novel building system based on natural fibres coreless-wound structural components for applications in architecture. J. Int. Assoc. Shell Spat. Struct. 65, 133–145. https://doi.org/10.20898/j.iass.2024.009.
Demir, C., Gökdoğan, O., Firat-Baran, M., 2022. Determination of energy usage and greenhouse gas emissions in lavender production. Rev. Investig. Univ. Quindío 34, 192–202. https://doi.org/10.33975/riuq.vol34nS5.1096.
Deng, Y., Tian, Y., 2015. Assessing the environmental impact of flax fibre reinforced polymer composite from a consequential life cycle assessment perspective. Sustainability. 7, 11462–11483. https://doi.org/10.3390/su70911462.
Deutscher Wetter Dienst, 2024. Jahresniederschlagshöhen in Baden-Württemberg, 1961–2023.
Dicker, M.P.M., Duckworth, P.F., Duckworth, P.F., Duckworth, P.F., Baker, Anna B., Baker, A.B., François, Guillaume, Francois, G., Hazzard, Mark K., Hazzard, M.K., Weaver, Paul M., Weaver, P.M., 2014. Green composites: a review of material attributes and complementary applications. Compos. Part -Appl. Sci. Manuf. 56, 280–289. https://doi.org/10.1016/j.compositesa.2013.10.014.
Dittenber, D.B., GangaRao, H.V.S., 2012. Critical review of recent publications on use of natural composites in infrastructure. Compos. Part Appl. Sci. Manuf. 43, 1419–1429. https://doi.org/10.1016/j.compositesa.2011.11.019.
Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., Garnier, C., 2023. A comprehensive review of natural fibers and their composites: an eco-friendly alternative to conventional materials. Results. Eng. 19, 101271. https://doi.org/10.1016/j.rineng.2023.101271.
European Confederation for Flax and Hemp, 2022. Life Cycle Assessment Scutched Fibre Report 2022.
European Environment Agency, 2007. Estimating the Environmentally Compatible Bioenergy Potential from Agriculture. Publications Office, LU.
Eurostat, 2022. HICP - annual data (average index and rate of change). https://doi.org/10.2908/PRC_HICP_AIND.
Eyupoglu, S., Merdan, N., 2021. Physicochemical properties of new plant based Fiber from lavender stem. J. Nat. Fibers 19, 9248–9258. https://doi.org/10.1080/15440478.2021.1982816.
Flanagan, 2020. Fact Sheet Horticulture 12. LAVENDER FLOWER AND OIL PRODUCTION.
FNR, 2008. Studie zur Markt- und konkurrenzsituation bei Naturfasern und NaturfaserWerkstoffen (Deutschland und EU).
Fachagentur Nachwachsende Rohstoffe, 2024. Fasernessel [WWW Document]. URL. https://pflanzen.fnr.de/industriepflanzen/faserpflanzen/fasernessel.

Fuchs, H., Albrecht, W., 2012. Vliesstoffe. Vliesstoffe. Wiley. https://doi.org/10.1002/9783527645862.fmatter.
Gil Pérez, M., Knippers, J., 2023. Integrative structural design of nonstandard Building systems: bridging the gap between research and industry. Technol. Des. 7, 244–261. https://doi.org/10.1080/24751448.2023.2246801.
Gil Pérez, M., 2024. Structural design challenges of bio-based composites and digital fabrication towards sustainable building systems. In: Block, P., Boller, G., DeWolf, C., Pauli, J., Kaufmann, W. (Eds.), Redefining the Art of Structural Design. Proceedings of the IASS 2024 Symposium, August 26-30, 2024. Zurich Switzerland, p. 153.
Gomez-Campos, A., Vialle, C., Rouilly, A., Sablayrolles, C., Hamelin, L., 2021. Flax fiber for technical textile: a life cycle inventory. J. Clean. Prod. 281, 125177. https://doi.org/10.1016/j.jclepro.2020.125177.
Grégoire, M., Bar, M., De Luycker, E., Musio, S., Amaducci, S., Gabrion, X., Placet, V., Ouagne, P., 2021. Comparing flax and hemp fibres yield and mechanical properties after scutching/hackling processing. Ind. Crops Prod. 172, 114045. https://doi.org/10.1016/j.indcrop.2021.114045.
Graupner, N., Lehmann, K.-H., Weber, D., Hilgers, H.-W., Bell, E., Walenta, I., Berger, L., Brückner, T., Kölzig, K., Randerath, H., Bruns, A., Frank, B., Wonneberger, M., Joulian, M., Bruns, L., Von Dungern, F., Janßen, A., Gries, T., Kunst, S., Müssig, J., 2020. Novel Low-Twist Bast Fibre Yarns from Flax Tow for High-Performance Composite Applications. Materials 14, 105. https://doi.org/10.3390/ma14010105.
Grundmann, E., 2009. Flachs – alte Kultur, neue Chance. Lebendige Erde.
Gurunathan, T., Mohanty, S., Nayak, S.K., 2015. A review of the recent developments in biocomposites based on natural fibres and their application perspectives. Compos. Part Appl. Sci. Manuf. 77, 1–25. https://doi.org/10.1016/j.compositesa.2015.06.007.
Halpern, B.S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J.L., Cottrell, R.S., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., Kuempel, C.D., McIntyre, P.B., Metian, M., Moran, D., Nash, K.L., Többen, J., Williams, D.R., 2022. The environmental footprint of global food production. Nat. Sustain. 5, 1027–1039. https://doi.org/10.1038/s41893-022-00965-x.
Harish, S., Michael, D.P., Bensely, A., Lal, D.M., Rajadurai, A., 2009. Mechanical property evaluation of natural fiber coir composite. Mater. Charact. 60, 44–49. https://doi.org/10.1016/j.matchar.2008.07.001.
Imbery, D.F., Friedrich, K., Niermann, D., Kaspar, F., Böttcher, F., Beyer, M., Posada, R., Leppelt, T., Lengfeld, K., Bär, F., Möller, T., Buchholz, S., Möller, J., 2024. Stand der Wissenschaft zu extremen wetterphänomenen im Klimawandel in Deutschland. Extrem Wetter Kongress, 2024.
Ingrao, C., Licciardello, F., Pecorino, B., Muratore, G., Zerbo, A., Messineo, A., 2018. Energy and environmental assessment of a traditional durum-wheat bread. J. Clean. Prod. 171, 1494–1509. https://doi.org/10.1016/j.jclepro.2017.09.283.
Institut für Pflanzenkultur e.K., 2019. Verbundvorhaben: entwicklung einer industriellen Bereitstellungskette von Brennnesseljungpflanzen bis zur Nesselfaser; Teilvorhaben 2: verbesserung der Wirtschaftlichkeit des Fasernesselanbaus durch synthetische Samen.
Ismail, M.R., Yassen, Ali.A.M., Afify, M.S., 2011. Mechanical properties of rice straw fiber-reinforced polymer composites. Fibers Polym. 12, 648–656. https://doi.org/10.1007/s12221-011-0648-5.
Kasmani, J., Samariha, A., 2011. Some chemical and morphological properties of wheat straw.
Kaur, G., Kander, R., 2023. The sustainability of Industrial Hemp: a literature review of its economic, environmental, and social sustainability. Sustainability. 15, 6457. https://doi.org/10.3390/su15086457.
Koronis, G., Silva, A., Fontul, M., 2013. Green composites: A review of adequate materials for automotive applications. Composites Part B: Engineering 44, 120–127. https://doi.org/10.1016/j.compositesb.2012.07.004.
Kozuharova, E., Vereecken, N.J., 2024. Lavender production in SE Dobrudja – intensive agriculture impacts pollinators' density and diversity. Euro-Mediterr. J. Environ. Integr. 9, 937–943. https://doi.org/10.1007/s41207-024-00498-z.
KTBL, 2024a. Leistungs-Kostenrechnung Pflanzenbau: sommerweizen [WWW Document]. URL. https://daten.ktbl.de/dslkrpflanze/postHv.html#Ergebnis (accessed 11.15.24).
KTBL, 2024b. Leistungs-Kostenrechnung Pflanzenbau: winterweizen [WWW Document]. URL. https://daten.ktbl.de/dslkrpflanze/postHv.html#Ergebnis (accessed 11.15.24).
KTBL, 2024c. Leistungs-Kostenrechnung Pflanzenbau: Miscanthus [WWW Document]. KTBL. URL. https://daten.ktbl.de/dslkrpflanze/postHv.html#Ergebnis (accessed 7.15.24).
Lesage-Meessen, L., Bou, M., Ginies, C., Chevret, D., Navarro, D., Drula, E., Bonnin, E., Del Río, J.C., Odinot, E., Bisotto, A., Berrin, J.-G., Sigoillot, J.-C., Faulds, C.B., Lomascolo, A., 2018. Lavender- and lavandin-distilled straws: an untapped feedstock with great potential for the production of high-added value compounds and fungal enzymes. Biotechnol. Biofuels 11, 217. https://doi.org/10.1186/s13068-018-1218-5.
Lewandowski, I., Clifton-Brown, J.C., Scurlock, J.M.O., Huisman, W., 2000. Miscanthus: european experience with a novel energy crop. BioMass BioEnergy 19, 209–227. https://doi.org/10.1016/S0961-9534(00)00032-5.
Lewandowski, I., Clifton-Brown, J., Trindade, L.M., Van Der Linden, G.C., Schwarz, K.-U., Müller-Sämann, K., Anisimov, A., Chen, C.-L., Dolstra, O., Donnison, I.S., Farrar, K., Fonteyne, S., Harding, G., Hastings, A., Huxley, L.M., Iqbal, Y., Khokhlov, N., Kiesel, A., Lootens, P., Meyer, H., Mos, M., Muylle, H., Nunn, C., Özgüven, M., Roldán-Ruiz, I., Schüle, H., Tarakanov, I., Van Der Weijde, T., Wagner, M., Xi, Q., Kalinina, O., 2016. Progress on optimizing Miscanthus Biomass production for the European bioeconomy: results of the EU FP7 Project OPTIMISC. Front. Plant Sci. 7. https://doi.org/10.3389/fpls.2016.01620.
Landesamt für Geologie, Rohstoffe und Bergbau, 2025. Bodenkunde Baden-Württemberg [WWW Document] URL https://lgrbwissen.lgrb-bw.de/bodenkunde.
Lundquist, L., Arpin, G., Leterrier, Y., Berthold, F., Lindström, M., Månson, J.-A.E., 2004. Alkali–methanol–anthraquinone pulping of *Miscanthus x giganteus* for thermoplastic composite reinforcement. J. Appl. Polym. Sci. 92, 2132–2143. https://doi.org/10.1002/app.20179.
Manian, A.P., Cordin, M., Pham, T., 2021. Extraction of cellulose fibers from flax and hemp: a review. Cellulose 28, 8275–8294. https://doi.org/10.1007/s10570-021-04051-x.
Martz, F., Ranta, A., Pyörälä, T., Liu, X., Nukari, A., Toivakka, R., Uusitalo, M., Maijala, V., Suomalainen, A., Jalava, T., Kankaanpää, S., Hannukkala, A., 2024. Arctic nettle, from Weed to money: Final report, Natural resources and Bioeconomy Studies. Natural Resources Institute Finland, Helsinki.
McCalmont, J.P., Hastings, A., McNamara, N.P., Richter, G.M., Robson, P., Donnison, I.S., Clifton-Brown, J., 2017. Environmental costs and benefits of growing *Miscanthus* for bioenergy in the UK. GCB Bioenergy 9, 489–507. https://doi.org/10.1111/gcbb.12294.
McCoy, J.-A., Davis, J.M., 1999. Lavender: History, Taxonomy, and Production [WWW Document]. URL https://newcropsorganics.ces.ncsu.edu/herb/lavender-history-taxonomy-and-production/ (accessed 12.1.25).
Meffo Kemda, M., Marchi, M., Neri, E., Marchettini, N., Niccolucci, V., 2024. Environmental impact assessment of hemp cultivation and its seed-based food products. Front. Environ. Sci. 12, 1342330. https://doi.org/10.3389/fenvs.2024.1342330.
Meisterling, K., Samaras, C., Schweizer, V., 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. J. Clean. Prod. 17, 222–230. https://doi.org/10.1016/j.jclepro.2008.04.009.
Mersch, J., Friese, D., Le Xuan, H., 2025. Toward the automation of the 3D robotic coreless filament winding process for high-performance composite materials with multiple reinforcement levels. Appl. Res. 4, e202400145. https://doi.org/10.1002/appl.202400145.
Mindermann, P., Gresser, G.T., 2023. Adaptive winding pin and hooking capacity model for coreless filament winding. J. Reinf. Plast. Compos. 42, 26–38. https://doi.org/10.1177/07316844221094777.
Mindermann, P., Gil Pérez, M., Knippers, J., Gresser, G.T., 2022a. Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding. Materials 15, 3260. https://doi.org/10.3390/ma15093260.
Mindermann, P., Gil Pérez, M., Knippers, J., Gresser, G.T., 2022b. Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding. Materials 15, 3260. https://doi.org/10.3390/ma15093260.
Mindermann, P., Lv, Y., Behera, M.P., Meot, R., Le Guen, M.-J., Singamneni, S., 2025. Exploring the sustainability potential of lightweight structures made from Phormium tenax fibers by hybrid coreless filament winding. Compos. Part Appl. Sci. Manuf. 199, 109168. https://doi.org/10.1016/j.compositesa.2025.109168.
Ministerium für Ernährung, 2013. Ländlichen Raum und Verbraucherschutz. Lockerung des Grünlandumbruchverbots zugunsten des Anbaus von Miscanthus.
Ministerium für Ernährung Ländlichen Raum und Verbraucherschutz, 2024. Robuste Kultur mit Mehrwert [WWW Document]. https://biomusterregionen-bw.de/,Lde/22451865.
Moll, L., Wever, C., Völkering, G., Pude, R., 2020. Increase of miscanthus cultivation with new roles in materials production—A review. Agronomy 10, 308. https://doi.org/10.3390/agronomy10020308.
Pan, M., Zhou, D., Bousmina, M., Zhang, S.Y., 2009. Effects of wheat straw fiber content and characteristics, and coupling agent concentration on the mechanical properties of wheat straw fiber-polypropylene composites. J. Appl. Polym. Sci. 113, 1000–1007. https://doi.org/10.1002/app.29789.
Panthapulakkal, S., Zereshkian, A., Sain, M., 2006. Preparation and characterization of wheat straw fibers for reinforcing application in injection molded thermoplastic composites. Bioreso. Technol. 97, 265–272. https://doi.org/10.1016/j.biortech.2005.02.043.
Pfeifer, S., Rechid, B., Bathiany, S., 2021. Klimaausblick Baden-Württemberg.
Röhricht, C., 1998. Flachs in Sachsen wirtschaftlich und umweltgerecht. Schriftenreihe Sächs. Landesanst. Für Landwirtsch.
Ramesh, M., Deepa, C., Kumar, L.R., Sanjay, M., Siengchin, S., 2022. Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: a critical review. J. Ind. Text. 51, 5518S–5542S. https://doi.org/10.1177/1528083720924730.
Sa, M., Zhang, B., Zhu, S., 2020. Miscanthus: beyond its use as an energy crop. BioResources 16, 5–8. https://doi.org/10.15376/biores.16.1.5-8.
Sadik, S.A., 2019. Production of Nettle (Urtica dioica).
Sarsour, J., Steinbach, G., Ewert, B., Stegmaier, T., Baz, S., Gresser, G.T., Weiler, C., 2023. New plant-based fibers from the residues of agricultural lavender plants. Melliand Int 1, 22–23.
Sazzini, L., 2024. Increasingly expensive flax in Europe [WWW Document]. PricePedia. URL https://www.pricepedia.it/en/magazine/article/2024/04/08/increasingly-expensive-flax-in-europe/ (accessed 2.26.25).
Scalabrin, E., Radaelli, M., Capodaglio, G., Pierobon, M., Del Vecchio, S., Buffa, G., 2024. Hemp cultivation opportunities for marginal lands development. PLoS. One 19, e0299981. https://doi.org/10.1371/journal.pone.0299981.
Schneider, C., Beckhaus, H., 2020. Entwicklung einer industriellen Bereitstellungskette von Brennnesseljungpflanzen bis zur Nesselfaser.
Shadhin, Mashiur Rahman, Raghavan Jayaraman, Ying Chen, Danny Mann, Wen Zhong, 2023. Natural biomass & waste biomass fibers – Structures, environmental

footprints, sustainability, degumming methods, & surface modifications 204, 117252–117252. https://doi.org/10.1016/j.indcrop.2023.117252.
Statistisches Landesamt Baden-Württemberg, 2024. Anbauflächen aller kultur- und Nutzungsarten [WWW Document]. URL. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/LF-NutzngKultFrucht.jsp (accessed 11.15.24).
Stavropoulos, P., Mavroeidis, A., Papadopoulos, G., Roussis, I., Bilalis, D., Kakabouki, I., 2023. On the path towards a "greener" EU: a mini review on flax (Linum usitatissimum L.) as a case study. Plants 12, 1102. https://doi.org/10.3390/plants12051102.
Stegmaier, T., Sarsour, J., Weiler, C., Zikeli, S., Kunert, R., Tippmann, M., 2024. AlbLavendel: potentiale zum anbau von Lavendel auf der schwäbischen Alb und zur gewinnung von Fasern.
Summerscales, J., Dissanayake, N.P.J., Virk, A.S., Hall, W., 2010. A review of bast fibres and their composites. Part 1 – Fibres as reinforcements. Compos. Part Appl. Sci. Manuf. 41, 1329–1335. https://doi.org/10.1016/j.compositesa.2010.06.001.
Sun, M., Xu, X., Wang, C., Bai, Y., Fu, C., Zhang, L., Fu, R., Wang, Y., 2020. Environmental burdens of the comprehensive utilization of straw: wheat straw utilization from a life-cycle perspective. J. Clean. Prod. 259, 120702. https://doi.org/10.1016/j.jclepro.2020.120702.
Thakur, V.K., Thakur, Manju Kumari, Thakur, M.K., Gupta, R., Gupta, Raju Kumar, Gupta, R.K., 2014. Review: raw Natural Fiber–Based polymer composites. Int. J. Polym. Anal. Charact. 19, 256–271. https://doi.org/10.1080/1023666x.2014.880016.
Thüringer Landesamt für Landwirtschaft und Ländlichen Raum, 2021. ANBAUTELEGRAMM Fasernessel (Urtica dioica L.) [WWW Document]. URL https://www.tlllr.de/www/daten/publikationen/anbautelegramm/at_fasernessel.pdf (accessed 4.8.24).
Tsalagkas, D., Börcsök, Z., Pásztory, Z., Gogate, P., Csóka, L., 2021. Assessment of the papermaking potential of processed Miscanthus × giganteus stalks using alkaline pre-treatment and hydrodynamic cavitation for delignification. Ultrason. Sonochem. 72, 105462. https://doi.org/10.1016/j.ultsonch.2021.105462.
Turunen, L., Van Der Werf, H.M.G., 2007. The production chain of hemp and flax textile yarn and its environmental impacts. J. Ind. Hemp 12, 43–66. https://doi.org/10.1300/J237v12n02_04.
Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, 2023. Klimawandel in Baden-Württemberg [WWW Document]. Baden-Württemberg.de. URL https://um.baden-wuerttemberg.de/de/klima-energie/klimawandel-und-anpassung/klimawandel (accessed 11.26.25).
Velimirovic, A., Jovovic, Z., Przulj, N., 2021. From neolithic to late modern period: Brief history of wheat. Genetika 53, 407–417. https://doi.org/10.2298/GENSR2101407V.
Viotti, C., Albrecht, K., Amaducci, S., Bardos, P., Bertheau, C., Blaudez, D., Bothe, L., Cazaux, D., Ferrarini, A., Govilas, J., Gusovius, H.-J., Jeannin, T., Lühr, C., Müssig, J., Pilla, M., Placet, V., Puschenreiter, M., Tognacchini, A., Yung, L., Chalot, M., 2022. Nettle, a long-known Fiber plant with new perspectives. Materials. (Basel) 15, 4288. https://doi.org/10.3390/ma15124288.
Vogl, C.R., Hartl, A., 2003. Production and processing of organically grown ®ber nettle (Urtica dioica L.) and its potential use in the natural textile industry: a review. Am. J. Altern. Agric. 18.
Wang, L., Littlewood, J., Murphy, R.J., 2013. Environmental sustainability of bioethanol production from wheat straw in the UK. Renew. Sustain. Energy Rev. 28, 715–725. https://doi.org/10.1016/j.rser.2013.08.031.
Witzel, C.-P., Finger, R., 2016. Economic evaluation of Miscanthus production – A review. Renew. Sustain. Energy Rev. 53, 681–696. https://doi.org/10.1016/j.rser.2015.08.063.
Zheljazkov, V.D., Cantrell, C.L., Astatkie, T., Jeliazkova, E., 2013. Distillation time effect on lavender essential oil yield and composition. J. Oleo Sci. 62, 195–199. https://doi.org/10.5650/jos.62.195.
Zwawi, M., 2021. A review on natural Fiber bio-composites, surface modifications and applications. Molecules. 26, 404. https://doi.org/10.3390/molecules26020404.