



Novel fibre value chains & ecosystem services  
from sustainable feedstocks

Deliverable 1.2 Agronomic & economic performance of  
primary production

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## 1. Introduction

This document outlines the agronomic and economic performance of the primary production for the research sites of the FIBSUN project. FIBSUN studies the production and use of the special crops cattail, reed, cardoon, hemp and short rotation wood biomass. These crops have potential in novel industrial applications and sustainable value chains with balanced environmental, economic and social outcomes. The crops were selected as suitable for marginal soils like rewetted peatlands, arid soils or contaminated soils. The aim of this report is to outline the specific challenges in the raw material production and solutions for the expansion of utilization of such materials.

Here we present an assessment of the long-term economic and agronomic performance of the primary production, based on structured on-site data collection carried out across multiple pilot sites. To ensure consistency and comparability, site managers at each location recorded yield and economic data using a standardized format.

Yield data were obtained either by harvesting representative sample plots or, depending on the crop, by recording total field yields. Crop quality was evaluated using methods tailored to the specific industrial applications of each crop. In addition, damages caused by diseases and pests were monitored once per growing season. Particular attention was given to identifying and assessing yield losses resulting from drought, water stress, and other extreme environmental events.

Alongside agronomic observations, economic data were compiled, e.g., the costs of fertilizers and other inputs, and income from harvest sales. The integration of these data enables the quantification of interdependencies between crop yields, management intensity and associated costs, biomass quality, and market prices. This comprehensive approach provides a scientific basis for evaluating the potential for upscaling sustainable primary production systems.



## 2. Agronomic & economic performance of primary production

### 2.1 Cattail

Within the FIBSUN project, cattail (*Typha latifolia*) is being investigated as a source of natural fibers for the production of insulation boards. Research activities focus on testing different harvesting times and developing an innovative fiber extraction method in order to optimize material quality and economic performance.

#### Site preparation, establishment and maintenance

The establishment and management costs of *Typha* paludiculture vary significantly depending on site conditions and the degree of hydrological modification required. To provide a representative overview, this section first presents typical values derived from the Dutch VIP-NL economic calculation tool for *Typha* cultivation, followed by the specific case of the Ankeveen pilot site where biomass for this study was harvested.

According to the VIP-NL economic tool (van den Akker & Fritz VIP-NL) and experience from several Dutch demonstration sites, *Typha* cultivation can often be established with relatively moderate investments when suitable wet conditions already exist. In such cases, minimal site preparation is required, and establishment costs remain limited.

Increasing revenues by ecosystem service payments for water storage or water purification are important factors to make *Typha* paludiculture economically attractive (Liu et al. 2023). However, the availability of land for *Typha* paludiculture is largely constrained by indirect and direct subsidies that currently favor drainage-based land uses; these include payments for air and water quality management, high water management costs, and direct agricultural subsidies, which perpetuate the status quo despite the long-term costs of land degradation. Consequently, lowering initial investment costs at the farm level is essential to create attractive starting conditions for transitioning to wet agriculture.

The main establishment strategies are typically distinguished: sowing and planting of cuttings, combined with different levels of site preparation. However, *Typha* can also establish spontaneously.

#### Sowing scenario (low establishment effort)

When the site already has sufficiently high groundwater levels, *Typha* can be established through direct sowing. Sowing costs are estimated at approximately 500 € per hectare per year during the first two years, resulting in total establishment costs of roughly 1,000 €/ha. This approach represents the lowest-cost option and assumes minimal hydrological intervention. In some instances, *Typha* may also establish spontaneously via rhizome expansion from adjacent stands, potentially eliminating establishment costs entirely if the site is connected to existing wetland populations.

#### Planting of cuttings (high establishment effort)



In some cases, planting Typha rhizomes or cuttings may be preferred to ensure rapid and uniform plant establishment, particularly when natural colonization is unlikely or when immediate biomass production is required. However, this method is significantly more expensive than sowing. The initial investment for planting is estimated at approximately 23,000 €/ha. When spread over a rotation period of 20 to 30 years, this equates to an annualized cost of roughly 1,000 €/ha. Such high upfront investments are generally only justified in settings where rapid yield ramp-up is critical or where the site lacks a seed/rhizome source for spontaneous establishment.

### Site preparation and water management

Decades of peatland drainage have severely degraded both soil structure and hydrology. Restoring these sites for paludiculture requires re-establishing specific conditions, such as a leveled (or slightly sloping) surface and water tables maintained close to the soil surface. In many jurisdictions, the costs associated with rehabilitating wet growing conditions may be eligible for coverage by the previous land user (similar to mining reclamation obligations) or by state actors, rather than the new farmer.

Where existing hydrological conditions are not suitable for paludiculture, additional groundworks are required to raise groundwater levels and create appropriate wetland conditions. Indicative values reported in the VIP-NL framework (van den Akker & Fritz VIP-NL) include:

- Groundworks and soil movement: approximately 6,700 €/ha per 40 yrs
- Soil import or modification: approximately 2,600 €/ha per 40 yrs
- Water inlet and outlet infrastructure: approximately 400 €/ha per 40 yrs

Collectively, these interventions may add approximately 9,000-10,000 €/ha to the initial investment (~250 €/ha/yr amortized over a 40-year horizon). Total establishment costs therefore depend strongly on the extent of hydrological modifications and site preparation required.

Under typical Dutch conditions, starting costs for Typha cultivation range from relatively modest investments on already wet sites (1,000-5,000 €/ha) to substantially high costs (>20,000 €/ha) where significant infrastructure modifications are necessary.

### Biomass quality and fiber yield variability

While total biomass yield is a primary economic driver, the quality of the fiber and the recovery rate during processing are equally critical for determining the final value of the crop. Typha biomass exhibits significant seasonal variation in moisture content, fiber length, and chemical composition, which directly influences the suitability for different end-uses (e.g., insulation boards vs. paper pulp).

### Seasonal differences in quality

Winter/autumn biomass is characterized by lower moisture content and lower protein levels. The fibers are generally longer and more lignified, making them ideal for insulation

board production where structural integrity is key. However, the lower protein content means less value can be extracted from the liquid fraction during processing.

Spring/summer biomass has significantly higher moisture content (up to 80–90% fresh weight) and higher protein concentrations. While these fibers are less typically used for insulation material, the high protein content makes this biomass highly suitable for biorefinery pathways where the "Typha juice" is valorized into protein concentrates, lipids, and pigments. The removal of sugars via juice extraction is a key quality enhancer, as it reduces the fiber's vulnerability to decomposition, thereby ensuring its suitability for high-performance insulation boards.

A critical distinction must be made between total dry matter yield and the extractable fiber yield. Pilot-scale thermo-mechanical pulping tests indicate that approximately 15% of the harvested dry matter is lost during the fiber extraction process due to the separation of non-fibrous parenchyma cells and soluble extracts. For example:

- Winter recovery: For a winter yield of 13.3 t DM/ha, the recoverable fiber is approximately 11.3 t/ha.
- Summer recovery: For a summer yield of 20.6 t DM/ha (before flower removal), the recoverable fiber is approximately 17.5 t/ha. After removing the flower fraction (1.2 t DM/ha), the remaining 19.4 t DM/ha yields approximately 16.5 t/ha of usable fiber.

Table 1. Average yields from 2024-2026, including three harvests from winter and two harvests from other seasons in different scenarios

| Scenario                       | Method                              | Fresh biomass harvested (t/ha) | Fresh biomass transported (t/ha) | Fresh fiber to dry (t/ha) | Fiber DM content (%) | Dry fiber yield (t/ha) | Dry fiber yield (t/ha) |
|--------------------------------|-------------------------------------|--------------------------------|----------------------------------|---------------------------|----------------------|------------------------|------------------------|
| Winter (business as usual)     | Harvest, transport, dry             | 40.2                           | 40.2                             | 40.2                      | 29                   | 13.3                   | 11.7                   |
| Winter (extruder)              | Harvest, press in field, dry        | 40.2                           | 26.4                             | 26.4                      | 45                   | 13.3                   | 11.9                   |
| Spring (biorefinery)           | Harvest, transport, extrude, refine | 86.1                           | 86.1                             | 31.2                      | 30                   | 16.3                   | 9.4                    |
| Summer (flowers + biorefinery) | Harvest, transport, extrude, refine | 82.6*                          | 78.0**                           | 41.9                      | 42                   | 19.4                   | 17.6                   |
| Autumn (extruder)              | Harvest, press in field, dry        | 85.2                           | 51.8                             | 51.8                      | 35                   | 19.6                   | 15.8                   |

\*yield with flowers

\*\*yield after flower harvest

Importantly, Typha demonstrated exceptional resilience throughout the monitoring period, with no recorded losses due to pests or diseases. This inherent hardiness contrasts with many annual crops and suggests that Typha offers a stable, low-risk

biomass supply, free from the biological uncertainties that often plague other paludiculture crops.

These quality differences dictate the optimal processing route for each scenario:

Pessimistic & Medium scenarios: Rely on winter harvesting where the fiber quality is stable and suitable for insulation. The 15% processing loss is accounted for in the operational cost models, as the lower moisture content reduces drying energy needs.

Optimal scenario: Leverages the summer biomass quality. Although the moisture content is higher (increasing transport volume), the biorefinery pathway avoids drying the entire mass. Instead, the high protein content of the juice fraction adds a secondary revenue stream that compensates for the higher logistics costs.

Therefore, the economic viability of Typha is not just a function of how much is harvested, but when it is harvested and how the specific quality profile is matched to the value chain.

#### Case study: Ankeveen pilot site, a high-cost scenario

The Typha biomass used in this project was harvested at the Ankeveen pilot site in the Netherlands. This site serves as a high-cost financial scenario, representing the upper bound of establishment costs. Unlike a typical commercial field, Ankeveen site was established as a multi-purpose restoration project prioritizing water storage, biodiversity, and knowledge exchange over paludiculture. As a result, only a limited portion of the site was dedicated to Typha cultivation, while other ecosystem services were prioritized over maximizing biomass production.

The production fields at Ankeveen were created in 2019 through significant landscape and hydrological modifications. Topsoil (0-10 cm) was moved to build small levees to form a basin, enabling the groundwater level to rise to approximately 15 cm above the soil surface.

According to Waterschap Amstel, Gooi en Vecht, (2025) the total estimated establishment cost for the pilot site was approximately 61,000 €. These costs included:

- Identification of a suitable location: 2,000 €
- Development of a production plan and ecological research: 16,000 €
- Soil modification and hydrological interventions (sod cutting and building levees, ditch modifications, pumps): 43,000 €
- Initial sowing, water level management, mowing operations, and compensation of farmer labour: 13,000 €

Of these expenditures, approximately 13,000 € represent recurring annual maintenance costs, mainly associated with water management and site operation.

These values are considerably higher than those observed at other Dutch Typha cultivation sites. The high costs primarily reflect the fact that the Ankeveen pilot site was designed as a multi-purpose restoration project, rather than an economically optimized biomass production system. Consequently, the establishment costs recorded there

should be interpreted as a special case rather than a representative benchmark for commercial Typha cultivation.

Experience from other Dutch sites indicates that where suitable wet conditions already exist and major hydrological modifications are not required, both establishment and maintenance costs can be significantly lower (Table 2).

Table 2. Cost comparison: Ankeveen vs. Commercial standard

| Cost Category             | Ankeveen (pilot)                                | VIP-NL Standard (Medium) |
|---------------------------|-------------------------------------------------|--------------------------|
| <b>Establishment</b>      | 61,000 € (Total Site)                           | 1,000 - 5,000 €/ha       |
| <b>Annual maintenance</b> | 13,000 € (Total Site)                           | 200 - 500 €/ha           |
| <b>Primary goal</b>       | Biodiversity & water storage Biomass production |                          |

### Economic performance: Three cost-revenue scenarios

To provide a robust assessment of Typha paludiculture, we show three distinct financial scenarios. These scenarios integrate the harvesting methods, yield data, processing logistics, and revenue streams discussed in the preceding sections. This approach presents the complete economic picture for each pathway, moving from the current pilot reality to a standard commercial operation, and finally to an optimized, integrated biorefinery model.

#### Scenario 1: Ankeveen pilot

This scenario represents the current reality of small-scale restoration projects, characterized by high pilot costs and inefficient logistics. At the Ankeveen site, winter harvesting is performed on a scale of less than one hectare using a Loglogic wetland mower (Fig. 1), resulting in exceptionally high harvesting costs of 5,300 €/ha (average of 3 years, Waterschap Amstel, Gooi en Vecht, 2025). These costs may be (substantially) higher than normal contracts as testing different harvesting logistics was part of a research program related to the Ankeveen pilot site. The biomass is transported with tipper truck (Fig. 1) and dried conventionally without volume reduction, leading to high logistics costs where transport and drying alone exceed 15,000 €/ha. Winter yields at this site are higher than on a typical commercial field, averaging 13.3 t DM/ha (Fig. 2), which, combined with a market price of approximately 756 €/t DM and standard Dutch subsidies totaling 3,118 €/ha, generates a total revenue of 13,173 €/ha. However, the total operational costs for this scenario exceed 20,576 €/ha. The result is a significant deficit of -7,403 €/ha, confirming that the current pilot model is economically unviable without external intervention or the introduction of high-value co-products.



Figure 1: Typha harvester (Loglogic wetland mower, left) and a tipper truck (right) in Ankeveen pilot site. In this scenario, biomass is directly transported without volume reduction from the field to a drying facility. Photos: Christian Fritz (left) and Sannimari Käärmelahti (right).

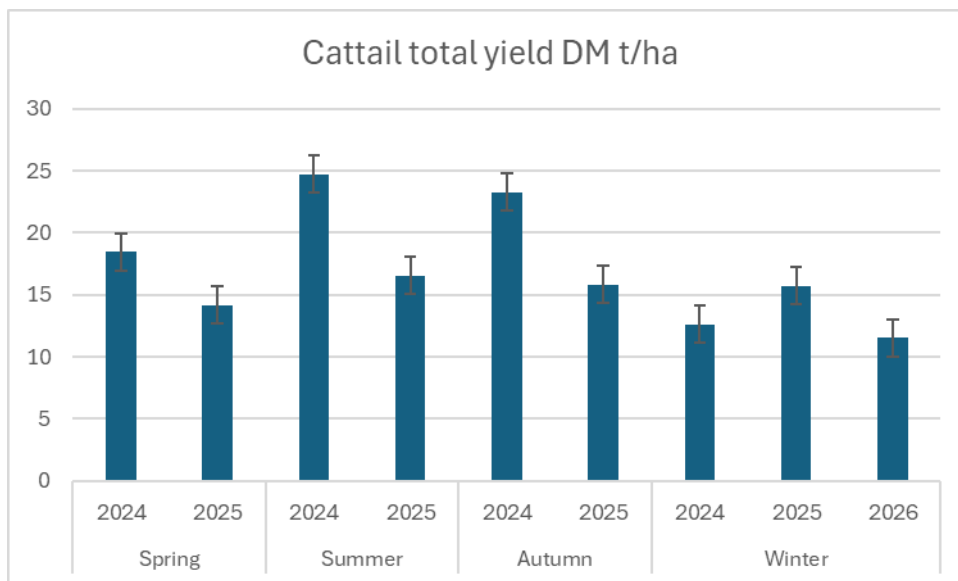


Figure 2: Typha yield in Ankeveen in different seasons 2024-2026

**Scenario 2: Medium (Optimized commercial standard)** The Medium scenario reflects a standard commercial farm operating at a viable scale, utilizing the cost and yield parameters defined in the Dutch VIP-NL economic calculation tool (van den Akker & Fritz VIP-NL). This scenario assumes a dedicated farm on a suitable wetland where hydrological conditions are already favorable, minimizing the need for expensive engineering. According to the VIP-NL model, standard establishment costs are significantly lower than the pilot site, ranging from 1,000 to 5,000 €/ha, and operational efficiencies are realized through larger field sizes. Mowing costs drop to approximately 3,000-3,500 €/ha due to better machinery utilization and reduced setup times. Transport

and drying costs follow standard commercial rates of approximately 80 €/t fresh biomass for transport and 300 €/t for drying. With a standard winter yield of 9 t DM/ha (equivalent to approximately 27 t fresh biomass), the total operational costs amount to roughly 13,500 €/ha. Revenue is generated from biomass sales at a farm-gate price of 220 €/t DM, yielding 1,980 €/ha, combined with the standard subsidy package of 3,118 €/ha, for a total revenue of 5,098 €/ha. However, the VIP-NL tool incorporates additional ecosystem service payments and carbon credits that bring the total annual revenue to approximately 14,500 €/ha when all income streams are accounted for. This results in a positive profit margin of approximately 1,000 €/ha, demonstrating that a well-managed commercial farm can achieve viability through standard practices alone. The key to this profitability lies in the combination of moderate yields, optimized logistics at scale, and the full utilization of available subsidies and ecosystem service payments.

### Scenario 3: Optimal (Flower harvest & field extrusion/biorefinery)

An Optimal scenario explores the upper bound of economic potential by introducing extrusion technology and integrating high-value co-product streams. The extrusion method, tested in the FIBSUN project, processes freshly harvested biomass through an extruder that removes a substantial fraction of water prior to drying (Fig. 3). By reducing the moisture content of the biomass before transport and drying, this approach reduces the mass that requires transportation and energy-intensive drying by 34%. This mass reduction translates directly into operational savings of roughly 1,100 €/ha for transport and 4,100 €/ha for drying, totaling a reduction of about 5,200 €/ha compared to the high-cost scenario. However, extrusion also introduces additional processing losses and requires specialized equipment. Current extrusion systems have energy requirements comparable to agricultural harvesters, and existing units are relatively heavy, which limits their direct use on wet paludiculture fields. This suggests that further technological development is required, particularly to design lighter mobile extrusion units that can operate under wetland conditions without causing soil damage. Should lighter, mobile extrusion units be developed to overcome current field limitations, the additional equipment and energy costs would be more than compensated for by the substantial reduction in logistics expenses.



Figure 3: Extruder being used on autumn biomass in Grassa biorefinery. Field extrusion would remove 34% of the moisture from the fresh weight substantially reducing the transportation and drying costs. Photo: Sannimari Käärmelahti.

In addition to reducing moisture content, extrusion produces a liquid fraction “Typha juice” containing dissolved nutrients, proteins and minerals. Preliminary research indicates that this juice contains some macronutrients (Table 3) even in autumn and winter. In case of a field extrusion, the liquid fraction could potentially be returned to the soil as a nutrient source, thereby recycling part of the harvested nutrients back into the system. Such an approach could reduce nutrient export from the field and decrease the need for external fertilization inputs, contributing to the circular management of paludiculture systems.

Table 3: macronutrient concentrations in Typha juice per season

| Season | N g/L | P g/L | K g/L |
|--------|-------|-------|-------|
| Spring | 1.1   | 0.3   | 1.6   |
| Summer | 0.7   | 0.2   | 1.9   |
| Autumn | 0.5   | 0.2   | 1.4   |
| Winter | 0.2   | 0.04  | 0.4   |

For summer and spring biomass, an alternative processing pathway may be more suitable. Due to the higher moisture content and higher protein concentrations (Fig. 4), typically present in actively growing plants, transporting the biomass to a centralized biorefinery could provide additional valorization opportunities. Grassa biorefinery (Netherlands), which currently processes grass biomass uses a comparable processing chain that could be applied to Typha. In this system, the harvested biomass is first

mechanically pressed or extruded to separate the juice fraction. The liquid fraction is then processed through several steps, including fiber filtration, thermal coagulation, and centrifugal separation using a decanter. This process yields a green protein fraction and a remaining “brown juice”. Approximately 25% of the protein contained in the dry biomass can be recovered as a protein concentrate, while additional components such as lipids and natural pigments may also be extracted.

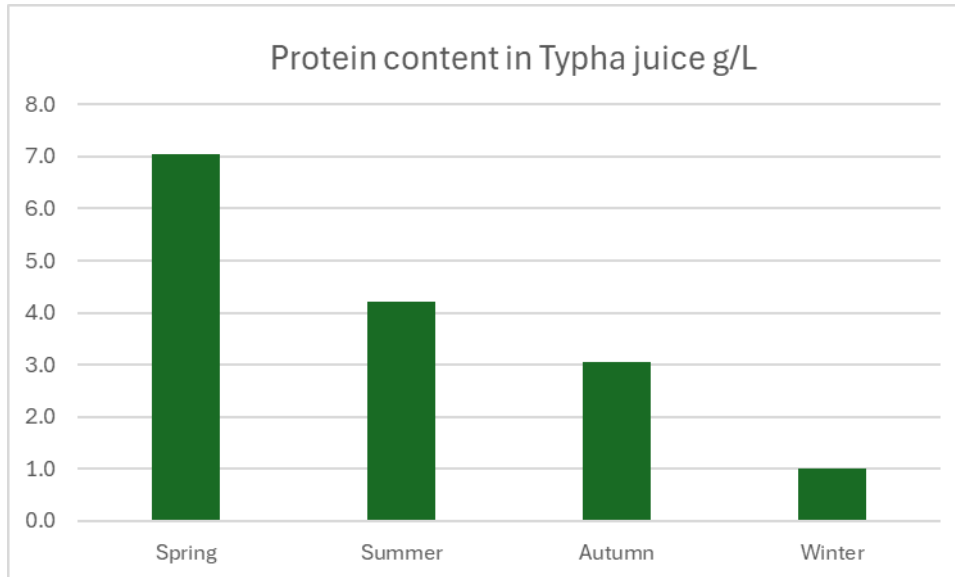


Figure 4: protein content g/L in the extracted Typha juice

The most optimal scenario explores the upper bound of economic potential by combining summer harvesting, biorefinery processing, and high-value flower sales. In this scenario, flowers are harvested first. As an example, in July 2025, a commercial partner (Ponda) harvested cattail flowers from the Helmond pilot site, paying approximately 3.50 €/kg for the material. From a 0.7 ha area, 2,900 kg of flowers were collected, corresponding to a yield of approximately 4,143 kg/ha and gross revenues of around 14,500 €/ha. Flower harvesting is labor-intensive, requiring approximately 207 man-hours per hectare at a productivity rate of 20 kg per person per hour. At an estimated labor cost of 15-20 €/hour, this adds 3,100-4,140 €/ha to operational costs. Even accounting for these labor expenses, the flower revenue generates a net surplus of approximately 10,400-11,400 €/ha.

Next step in this pathway would be to target the higher, protein-rich summer yields of 20.6 t DM/ha (Fig. 2), from which 19,4 t/ha remains after the flower harvest. The biomass would be transported to a centralized biorefinery where the biomass is processed to separate fiber from a nutrient-rich juice fraction. While transport costs are higher due to the volume of fresh biomass, the biorefinery process avoids drying the entire mass, focusing energy only on the fiber fraction. When combining the flower profits with the summer biomass revenue of 14,666 €/ha (using 250 €/t FW) and the standard subsidies of 3,118 €/ha, the total revenue reaches approximately 32,284 €/ha. Despite the higher operational costs associated with biorefinery transport and flower labor, the substantial revenue from flowers drives the balance to a positive surplus of +5,600 €/ha. Even with conservative adjustments for labor costs, the scenario maintains a healthy margin, proving that diversification is the key to robust profitability.

It is also important to recognize that the economic potential of the spring route next to the summer as they extend beyond flowers and fiber. The biorefinery pathway enables the valorization of additional product streams, such as protein concentrates, lipids, and natural pigments extracted from the "Typha juice" fraction. While the current economic model focuses on fiber and flowers, the ability of future biorefineries to monetize these soluble compounds could further enhance the profitability of the Optimal scenario. Therefore, the long-term economic viability of spring and summer routes depends strongly on the technological maturity and market readiness of these co-product extraction processes. As these markets develop, the revenue potential of the summer harvest could increase significantly, making the integrated biorefinery model even more robust. Different harvesting and processing strategies depending on the season and the intended value chain are visualized in Fig. 5.

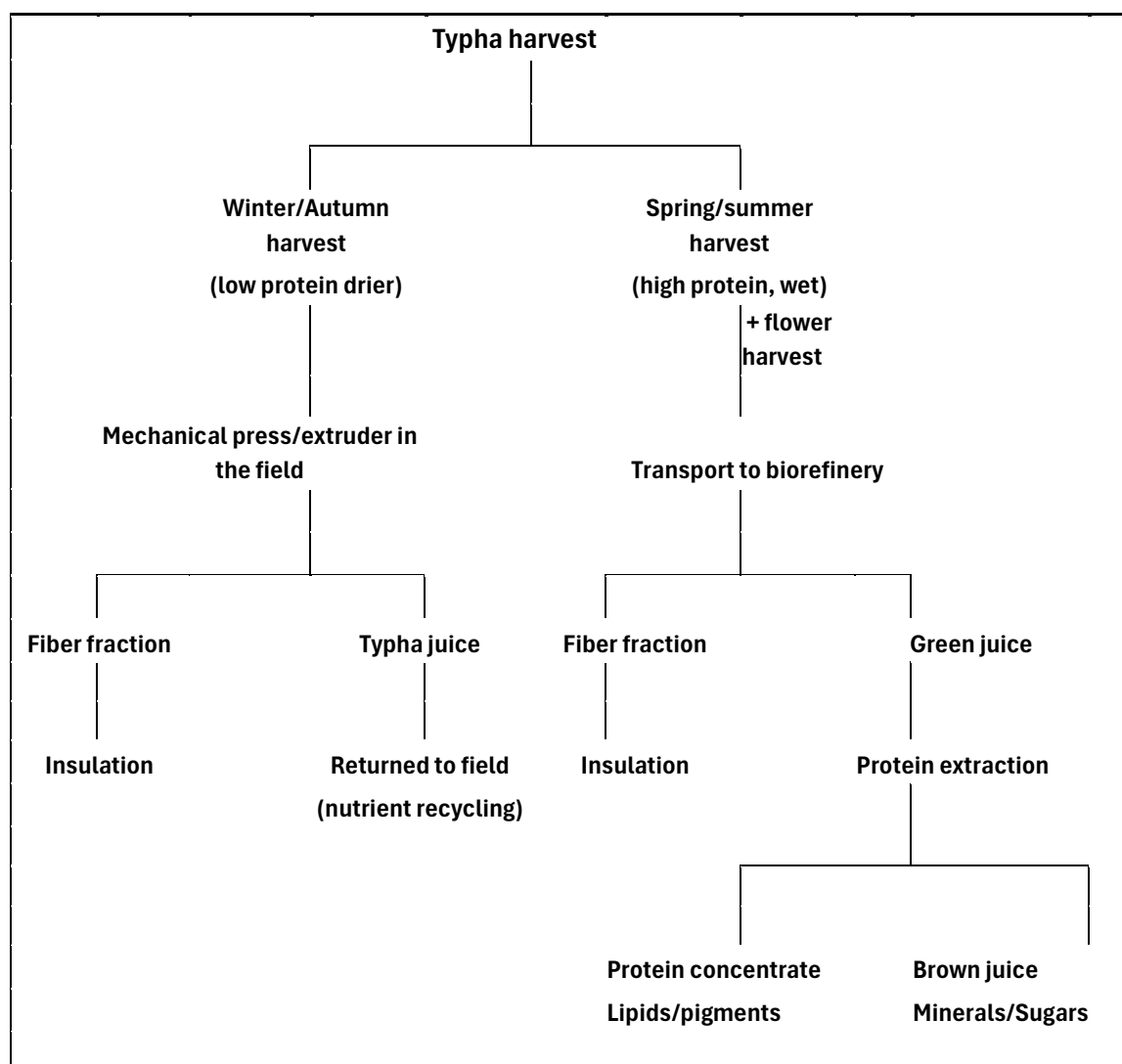


Figure 5. Conceptual model of processing pathways for Typha biomass using the extruder method. Winter/autumn biomass could be extruded in the field to reduce the fresh weight and protein-rich spring/summer biomass could be transported to a biorefinery. Flower harvest in the summer would increase profits even more.

### Comparative summary of economic scenarios

The economic performance of Typha paludiculture varies drastically depending on the operational model. To illustrate this, we compare four distinct pathways: the current pilot reality (Pilot), a standard commercial operation (Medium), a technologically optimized commercial operation (Medium Optimized), and a fully integrated biorefinery model (Optimal), (Table 4).

The high-cost (Pilot) scenario highlights the structural unviability of small-scale, inefficient operations, resulting in a deficit of -7,403 €/ha. The Medium (Standard) scenario, based on VIP-NL parameters, demonstrates that scaling up and utilizing standard subsidies allows for a modest positive margin of approximately +1,000 €/ha.

Crucially, the Medium (Optimized) scenario reveals the transformative power of field extrusion. By mechanically removing water immediately after harvest, transport and drying volumes are reduced by 34%, slashing operational costs by nearly 5,000 €/ha. This technological intervention could lift the profit margin to +5,700 €/ha, making it nearly as profitable as the complex summer-flower model without the associated market risks, however, the suitable lightweight technology does not exist yet.

Finally, the Optimal scenario combines high summer yields with flower sales and biorefinery processing, achieving a surplus of +5,684 €/ha. The comparison confirms that while diversification (flowers) is a powerful driver of profit, technological optimization (extrusion) is equally critical for securing economic viability in standard winter harvesting systems.

Table 4. Economic comparison of Typha paludiculture scenarios (€/ha/year).

| Indicator                      | Pilot (Ankeveen)     | Medium (VIP-NL Standard)  | Medium (Optimized w/ Extrusion) | Optimal (Summer + Flowers)     |
|--------------------------------|----------------------|---------------------------|---------------------------------|--------------------------------|
| <b>Harvest Strategy</b>        | Winter (Small scale) | Winter (Commercial scale) | Winter (Commercial + extrusion) | Summer (Biorefinery + flowers) |
| <b>Biomass yield (DM)</b>      | 13.3 t/ha            | 9.0 t/ha                  | 9.0 t/ha                        | 19.4 t/ha (after flowers)      |
| <b>Flower revenue</b>          | 0 €                  | 0 €                       | 0 €                             | 14,500 €                       |
| <b>Total revenue</b>           | 13,173 €             | 14,500 €                  | 14,500 €                        | 32,284 €                       |
| <b>Total operational costs</b> | 20,576 €             | 13,500 €                  | 8,800 €                         | 26,600 €                       |
| <b>Net balance</b>             | -7403* €             | 1,000(to 1,660*) €        | 5,700 €                         | 5,684 €                        |
| <b>Viability status</b>        | Pilot funding        | (Marginally) viable       | Highly viable                   | Highly viable                  |

\*Net balance is without additional payments for the cattail farmer to operate and maintain the site. In case of the pilot these payments amounted to 5000 € annually to compensate the farmer for research and pilot related communication and operational activities. In the Medium case (VIP-NL) extra annual revenues were estimated to reach 660 €.

### Market dynamics and future outlook

The economic viability of Typha paludiculture is closely tied to evolving market dynamics in the fiber and paper sectors. Recent insights from the Paludi4All Horizon project highlight the development of advanced, site-specific business models for Typha, which offer granular financial data that complements the broader VIP-NL framework. While these models require translation and integration, they underscore the importance of using localized, up-to-date economic tools for accurate forecasting.

Furthermore, the global paper market is undergoing a significant transformation that presents a unique opportunity for Typha fiber. As digitalization reduces the volume of printed matter, the supply of recyclable paper fibers is shrinking, driving up the price of raw recycled paper to approximately 600 €/ton. With a typical 40% mass loss during the recycling process, the demand for high-quality alternative fibers is intensifying. Typha, with its long fibers and suitability for paper and insulation applications, is well-positioned to fill this gap. Unlike traditional wood pulp, Typha offers a sustainable, wetland-compatible alternative that can command premium pricing in a market where recycled fiber is becoming scarce.

### Conclusion on viability

Overall, cattail is a low-risk, low-input crop, but its economic success is entirely dependent on market segmentation and logistics. Overall, cattail is an interesting crop for marginal carbon rich soils, ranging from low-input to high input crop. Cattail's economic success is, however, entirely dependent on site conversion costs, market segmentation and logistics. The small pilot scale with high site investment and intensive management is insufficient to cover costs, exacerbated by high harvesting logistics expenses. However, the "Medium" scenario proves that the insulation market (FIBSUN's focus) is a viable standalone pathway, generating a potential profit ranging from 1000 € - 5,000 €/ha including carbon market payments. The "Optimal" scenario further suggests that future commercial operations should aim to capture the full value chain by sorting biomass for both insulation and high-value fibers (textile fibers), maximizing the return on the high-input cultivation system. For cattail the adoption of cost-efficient establishment using the wettest parts and culturing from seeds or spontaneous plant establishment remains crucial. As cattail is a permaculture biomass crop its viability rests on efficient harvesting, proximity to the processor, and access to the right market segments.

## 2.2 Reed

Within the FIBSUN project, reed fibers from the Tuhkanen site (Fig. 6) in Finland are being evaluated as a raw material for the production of insulation boards. The site is located in the municipality of Kauhajoki and consists of a rewetted peatland ecosystem. Covering approximately 4 hectares, the area was previously drained and exploited for peat extraction until 2019. In 2022, hydrological restoration measures were implemented by damming the site to restrict water outflow, which resulted in a significant rise in the groundwater level, now remaining close to the soil surface. Diverse wetland vegetation



has developed at the site over these years, and FIBSUN project monitors the originally modest but well-growing reed stand shown in Fig. 6.

### Site preparation, establishment and maintenance

The hydrological restoration required one-off investments associated with rewetting measures, including dam construction and site modifications. The total reported cost of these interventions amounts to 11,532 €, corresponding to approximately 2,883 € per hectare. These costs represent initial capital expenditures necessary to provide societal services related to rewetted peatland and, in the next step offer options for reed establishment and long-term biomass production.



Figure 6. An aerial photograph of the site showing the spread of the reed stand in 2023 (orange line) and 2026 (green line). The black soil represents the situation before rewetting. Photo: Henri Honkanen

Following rewetting, reed vegetation established spontaneously, supported by consistently high water levels. As a result, the site requires minimal management interventions. No regular agronomic maintenance is currently needed, which keeps operational costs at a very low level compared to conventional agricultural systems.

### Harvesting and operational costs in Kauhajoki and generally in Finland

Harvesting operations constitute the main recurring cost associated with reed production. This site has not been harvested in full scale yet and was used only for estimating the capacity of the reed stand to spread and the yield level. The biomass used in FIBSUN was harvested as bundles from a lakeside using a Yucheng harvesting machine (Yucheng Agri Machinery Co., Ltd.), and the estimates regarding the harvest cost are based on that harvest and average winter reed harvest costs in Finland. Total

harvesting costs can be estimated at approximately 7,000 €, corresponding to about 1,750 € per hectare. However, detailed information on the composition of these costs (e.g. labour, machinery, fuel, transport, and processing) is currently limited, which constrains a comprehensive assessment of the economic performance of reed biomass production at this site.

Table 5. Cost breakdown for reed management operations in Finland, ranging from basic harvesting to full logistics chains.

| Operation           | Cost range | Unit             | Source                                                                                              |
|---------------------|------------|------------------|-----------------------------------------------------------------------------------------------------|
| Harvesting          | 600-1000   | €/ha             | Compilation of harvest costs from various sites (Ajosenpää 2014)                                    |
| Harvesting + piling | 1500-2000  | €/ha             | Finnish reed management studies (Valonia 2016; Turku U. of Applied Sciences 2023)                   |
| Transport           | approx. 8  | €/m <sup>3</sup> | Compilation of Finnish projects (strongly dependent on distance), Turku U. of Applied Sciences 2023 |

Reported harvesting costs for reed in Finland in general range from approximately 600 to 1,000 €/ha for mowing alone, while harvesting combined with piling or bundling may increase costs to 1,500-2,000 €/ha (Table 5). Transport costs are typically estimated at approx. 8 €/m<sup>3</sup> of biomass, depending on distance and logistics. This site is more easily accessible than most lakesides, and thus the costs could be lower than average if reed was harvested in full scale.

### Reference economic conditions (Germany)

To provide a comparison for reed biomass production, reference values from Germany were reviewed using the MoorWertRechner (Moor and More) paludiculture economic assessment tool. The model describes reed production on rewetted peatlands where the crop establishes naturally under permanently high groundwater levels. Under these conditions, no annual soil preparation or agronomic inputs are required, and the only recurring management activity is harvesting and biomass transport.

The economic structure of reed paludiculture is therefore dominated by harvesting and logistics rather than cultivation costs. Typical biomass yields in German reference scenarios range between 5 and 10 t dry matter per hectare, depending on site productivity. Harvesting is carried out with specialized mowing equipment suitable for wet soils, with costs typically ranging between 1,200 and 2,000 €/ha. Transport costs depend strongly on the distance to the processing facility and generally range from 10 to 25 €/t biomass. In addition, area-based agricultural subsidies of around 100 €/ha may contribute to overall revenues (Table 6).

Revenues from reed biomass depend on the intended end use (e.g. insulation materials, energy or fiber products) and typically range between 120 and 200 €/t dry matter. Under favorable conditions, high yields, short transport distances and stable biomass markets, reed paludiculture can be economically competitive due to its low input requirements. However, profitability remains highly sensitive to logistics and transport distances.

Table 6: Typical economic parameters for reed paludiculture based on German MoorWertRechner scenarios.

| Parameter          | Typical range            | Notes                           |
|--------------------|--------------------------|---------------------------------|
| Biomass yield      | 5-10 t DM/ha             | Depends on site productivity    |
| Harvest cost       | 1,200-2,000 €/ha         | Specialized mowing on wet soils |
| Transport cost     | 10-25 €/t biomass        | Strongly dependent on distance  |
| Biomass price      | 120-200 €/t DM           | Depends on end use              |
| Area-based subsidy | approx. 100 €/ha         | Typical agricultural support    |
| Main cost drivers  | Harvesting and transport | Minimal agronomic inputs        |

Overall, reed represents a low-input paludiculture system with relatively simple management requirements. However, its economic performance depends strongly on logistics, particularly transport distance and harvesting efficiency.

### Yields and biomass quality

Yield assessments for the reed (*Phragmites australis*) stand at the Tuhkaneva pilot site were conducted based on winter harvests carried out between 2024 and 2026. The data reflects the productivity of the naturally established reed population following the hydrological restoration measures implemented in 2022.

The average total dry matter (DM) yield, calculated after accounting for harvest losses, was determined to be  $11.8 \pm 4.2$  t DM/ha (Table 7). This yield level is notably robust for a paludiculture system on rewetted peatland and falls within the upper range of typical German reference scenarios (5-10 t DM/ha), suggesting that the Tuhkaneva site possesses high productive potential despite its spontaneous establishment. The standard deviation ( $\pm 4.2$  t/ha) indicates some spatial variability in biomass density across the 4-hectare site, which is expected in natural reed stands where micro-topography and water depth variations influence growth rates. Harvesting cost per tDM may decrease when low-productive areas/spots are left out from harvesting, especially at sites large enough to harvest 2-3 consecutive days. No marked yield losses were observed due to pests, diseases or herbivory during the study years.

A critical metric for the FIBSUN value chain is the recoverable fiber fraction. Following thermo-mechanical pulping of the harvested biomass, the extracted fiber yield averaged  $10.1 \pm 3.6$  t DM/ha. This corresponds to a fiber extraction efficiency of approximately 86% of the total harvested dry matter. The remaining 14% loss during the pilot-scale pulping process is attributed to the separation of non-fibrous components (such as parenchyma cells and soluble extracts) and mechanical attrition.

Table 7: Details of yield (average of winter harvests in 2024-2026)

| Fraction DM                                  | Yield      | Unit |
|----------------------------------------------|------------|------|
| <b>Total yield (after losses in harvest)</b> | 11.8 ± 4.2 | t/ha |
| <b>Extracted fiber total*</b>                | 10.1 ± 3.6 | t/ha |

\*Loss in pilot-scale thermo-mechanical pulping 14%

The high ratio of extractable fiber to total biomass (approx. 86%) is a significant advantage for insulation board production, as it minimizes waste generation and maximizes the utilization of the harvested resource. Compared to other paludiculture biomass like biorefined cattail, where fiber content can vary significantly with harvesting season, the reed stand at Tuhkaneva demonstrates consistent fiber availability throughout the winter harvest window.

Yields showed a marked increase in 2026 (15.4 t DM/ha) compared to the previous two years (~10.0 t DM/ha, Fig. 7). Still, the mean yield of nearly 12 t DM/ha provides a solid economic baseline, showing that rewetted peatlands can serve as productive sources of industrial fiber without the need for intensive agronomic inputs.

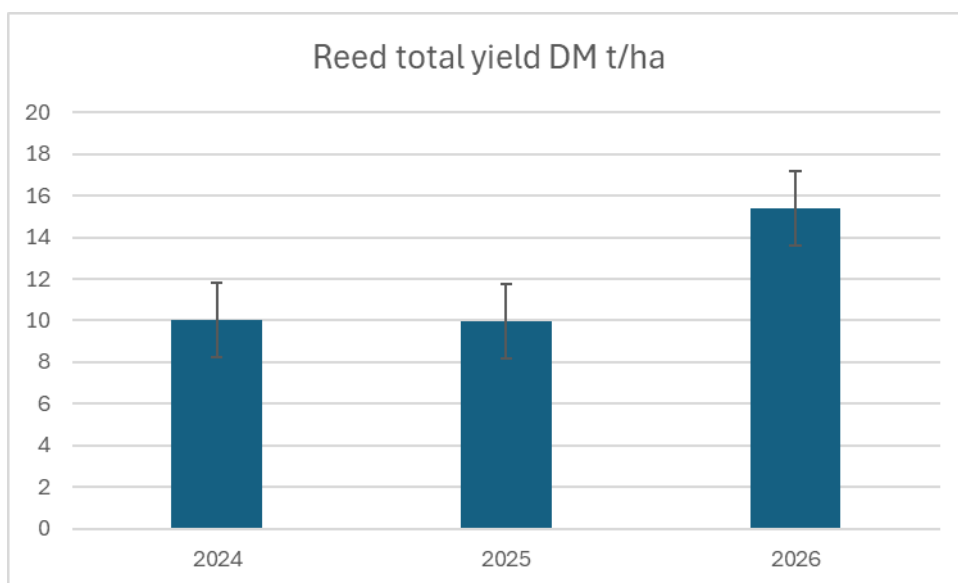


Figure 7: The annual variation in total dry matter yield across the monitoring period.

### Economic interpretation: three financial scenarios for reed

Table 7 indicates that the market value of reed biomass in Finland varies significantly depending on the intended end use. The reported price range spans approximately 0.04-1.14 €/kg dry matter, reflecting the large differences between low-value energy applications and higher-value products such as thatching materials.

Table 7. Indicative price ranges for reed biomass in Finland depending on end use.

| End use       | Product form  | Typical unit price           | Approx. price (€/kg DM)  |
|---------------|---------------|------------------------------|--------------------------|
| Thatching     | Reed bundles  | 3-5 € per bundle             | approx. 1.14 €/kg DM     |
| Insulation    | Bulk biomass  | approx. 590 € per ton        | Approx. 0.6 €/kg DM      |
| Chopped reed  | Loose biomass | approx. 166 €/m <sup>3</sup> | approx 0.8 €/kg DM       |
| Energy use    | Bulk biomass  | approx. 380 €/ha equivalent  | approx 0.04 €/kg DM      |
| Growing media | Reed bales    | approx. 10 € per bale        | approx 0.06-0.11 €/kg DM |

The economic viability of reed paludiculture is highly sensitive to the end-use market and logistics. Reed does not currently benefit from agricultural subsidies in Finland, making the balance between harvesting costs and biomass price the critical determinant of profitability. To assess this, we modeled three distinct scenarios ranging from a worst-case energy market to an optimized mixed-stream approach (Table 8).

Table 8. Economic comparison of reed paludiculture scenarios (€/ha/year)

| Indicator                      | Pessimistic (Energy grade) | Medium (Insulation)        | Optimal (Mixed stream)         |
|--------------------------------|----------------------------|----------------------------|--------------------------------|
| <b>Market destination</b>      | Energy / Bulk Biomass      | Insulation Boards (FIBSUN) | 50% Thatching + 50% Insulation |
| <b>Biomass price</b>           | 0.04 €/kg DM (40 €/t)      | 0.60 €/kg DM (600 €/t)     | Mixed: ~0.87 €/kg DM avg       |
| <b>Yield (DM)</b>              | 8.0 t/ha (Conservative)    | 11.8 t/ha (FIBSUN avg)     | 11.8 t/ha                      |
| <b>Total revenue</b>           | 320 €                      | 7,080 €                    | 10,266 €                       |
| <b>Harvesting cost</b>         | 1,000 € (Mowing only)      | 1,750 € (Mowing + piling)  | 1,750 € (Mowing + sorting)     |
| <b>Transport cost</b>          | 800 € (Long distance)      | 250 € (Moderate distance)  | 250 € (Moderate distance)      |
| <b>Total operational costs</b> | 1,800 €                    | 2,000 €                    | 2,000 €                        |
| <b>Net balance</b>             | -1,480 €                   | 5,080 €                    | 8,266 €                        |
| <b>Viability status</b>        | Non-viable                 | Viable                     | Highly viable                  |

*Note: Prices are based on indicative Finnish market rates (Table 7). Transport costs assume ~8 €/m<sup>3</sup>. The "Pessimistic" scenario assumes long-distance transport to energy plants, while "Medium" and "Optimal" assume moderate distances to insulation or thatching processors. The "Optimal" scenario assumes 50% of the biomass is sorted into thatching bundles (1.14 €/kg DM) and 50% into insulation fiber (0.60 €/kg DM).*

### Scenario 1: Pessimistic (Energy grade)

In this scenario, reed is harvested solely for low-value energy applications (bulk biomass), often requiring transport over long distances to centralized power plants. With a market price of approximately 40 €/t DM and conservative yields of 8 t/ha, the total revenue is only 320 €/ha. When combined with mowing costs (~1,000 €/ha) and high transport costs (~800 €/ha), the total operational costs reach 1,800 €/ha. This results in a significant deficit of -1,480 €/ha. The deficit would be reduced to -930 €/ha in cases of moderate distance transport. This confirms that reed cultivation cannot be economically sustained if the only market is energy production, especially when logistics are inefficient.

### Scenario 2: Medium (Insulation only)

This scenario reflects the primary goal of the FIBSUN project: producing raw material for insulation boards. With a yield of 11.8 t/ha and a market price of approximately 600 €/t DM (0.60 €/kg), the revenue rises to 7,080 €/ha. Harvesting costs increase to 1,750 €/ha to include piling and handling for fiber quality. Crucially, by locating processing facilities at a moderate distance, transport costs are reduced to 250 €/ha. Despite the lack of agricultural subsidies, the operation achieves a solid positive balance of +5,080 €/ha. This demonstrates that the insulation market alone is sufficient to make reed paludiculture viable, provided that transport distances are kept short and yields are stable.

### Scenario 3: Optimal (Mixed stream: thatching + insulation)

The highest economic potential is realized by diversifying the output. In this scenario, 50% of the biomass (the straightest, longest stems) would be sorted into high-value thatching bundles, commanding a price of 1,140 €/t DM. The remaining 50% would be directed to insulation fiber production at 600 €/t DM. This mixed approach generates a total revenue of 10,266 €/ha. While the sorting and bundling labor is included in the harvesting cost, the premium price for thatching drives the net balance to +8,266 €/ha. This scenario highlights that while the insulation market alone provides a solid baseline, integrating high-value niche markets like thatching can significantly boost profitability, nearly doubling the margin compared to insulation alone.

### Conclusion on viability

Overall, reed is a low-risk, low-input crop, but its economic success is entirely dependent on market segmentation and logistics. The "Pessimistic" energy market is insufficient to cover costs, exacerbated by high transport expenses. However, the "Medium" scenario proves that the insulation market (FIBSUN's focus) is a viable standalone pathway, generating a robust profit of over 5,000 €/ha without subsidies. The "Optimal" scenario further suggests that future commercial operations should aim to capture the full value chain by sorting biomass for both insulation and high-value thatching, maximizing the return on the low-input cultivation system. Crucially, unlike cattail, reed does not require

expensive establishment or complex processing technologies; its viability rests on efficient harvesting, proximity to the processor, and access to the right market channels.

## 2.3 Cardoon

Cardoon (*Cynara cardunculus*) is being investigated within the FIBSUN project as a potential source of lignocellulosic fibers derived from stalks and leaves for the production of textile yarn. Cardoon is a perennial Mediterranean crop characterized by high biomass production, deep root systems, and strong tolerance to drought and poor soils, which makes it particularly suitable for low-input and marginal agricultural areas.

### Site preparation, establishment and maintenance

Once established, cardoon requires limited agronomic interventions. The crop is sown only once, as plants regenerate annually from their root systems, which significantly reduces establishment costs compared to annual crops. After implantation, field preparation is minimal and mainly limited to annual weeding operations to maintain site accessibility and reduce competition from spontaneous vegetation. These operations result in average costs of approximately 180 €/ha/year.

At this location, irrigation systems were installed to ensure stable and sufficient biomass production. Water is supplied from a local groundwater source, with pumping systems powered by solar panels. This configuration results in relatively low operational and maintenance costs. The main recurring irrigation-related expense is the annual replacement of degraded hoses in the watering system, estimated at approximately 150€/ha. In addition to irrigation, cardoon plants are fertilized using organic or mineral fertilizers (e.g. compost, manure, or NPK fertilizers), resulting in additional costs of approx. 100 €/ha. Combined with weeding, total annual management costs remain relatively low, highlighting the suitability of cardoon as a low-maintenance perennial crop.

### Harvesting and operational costs

Harvesting of cardoon biomass typically takes place in late spring or summer, depending on climatic conditions and the targeted plant components. At the current site, harvesting is performed manually (Fig. 8). Harvesting the stalks for biomass requires approximately 24 man-hours per hectare (based on a 0.5 ha plot harvested in 12 hours by two workers). According to the 2025 Portuguese agricultural collective agreement (Confederação dos Agricultores de Portugal & SETAAB, 2023), the minimum hourly rate for an agricultural worker (Level 5) is 6.13 €, resulting in an estimated labour cost of approximately 147 € per hectare for stalk harvesting.

It is important to note that the biomass harvest is performed only after the main value chain of the plant (flowers and seeds) is finished. While it is theoretically possible to harvest both simultaneously, flowers are highly sensitive and much easier to harvest while the stems are still vertical. Therefore, the flower and stem biomass must be harvested separately. According to local landowners, harvesting flowers on a 1-hectare site takes approximately 32 man-hours (two days for two workers), adding an estimated 196 € per hectare to the total harvesting operations if both value chains are pursued.



Figure 8. Cardoon harvesting in Ourique, Portugal. Harvesting was conducted manually for FIBSUN project. Photo: Filipe Soutinho

### Yields and biomass quality

From an economic perspective, cardoon already benefits from an established value chain for flowers and seeds. Flowers are marketed at prices ranging from approximately 25 to 45 €/kg, while seeds are sold at around 2 €/kg for industrial purposes and up to 100 €/kg when selected for sowing material. In contrast, the market value of cardoon stalks is not yet clearly defined. Furthermore, the integration of multiple value chains is currently limited, meaning that farmers generally need to decide in advance whether to prioritize flower, seed, or stalk production. This constraint affects the economic feasibility of valorizing stalks for fiber applications and highlights the need for further development of integrated processing and market structures.

For acquiring the yield data for the FIBSUN project, the harvest of the stalks was conducted manually. The stalks were cut at their base using electric scissors, after which they were manually cleaned to remove all dead leaves and dry thorns. The cleaned stalks were then tied together and placed in large plastic bags in preparation for shipping. The results from the sampled plots were then extrapolated to calculate the yield in kg/ha.

Significant yield losses were observed during one of the harvests due to pest pressure, with up to 90% of production affected by butterfly larvae (Fig. 9). The species responsible is likely to be identified among common *Lepidoptera* pests associated with cardoon and related *Asteraceae* crops. This level of damage underlines the importance of pest monitoring and integrated pest management strategies to ensure stable production and reduce economic risks. One reason for the pest infestation could have been the fact that the fiber extraction was possible only three days after the harvest.



Figure 9: Butterfly larvae infested cardoon stalk. Cardoon stalks can serve as nesting and hatching habitats for insect communities. This led to 90% yield losses. Photo: Filipe Soutinho

The September harvest was conducted at a different site, located more than 400 km away from the main harvest site. Despite the distance, both sites exhibited significant losses due to insect contamination. This widespread presence suggests that infestation may not merely be a pest issue, but rather an indication that cardoon stalks serve as vital nesting and hatching habitats for local insect communities. This raises important ecological questions regarding the viability of removing this biomass from the field, as its presence appears to be a precursor for local biodiversity.

Furthermore, the severity of the damage observed in the August harvest was exacerbated by a delay in processing. The large distance between the harvesting site and the processing facility led to a three-day delay before fiber extraction could occur. This delay provided the insect eggs present in the stalks with sufficient time to develop and eventually hatch, resulting in the observed 90% yield loss. In contrast, when fiber extraction was performed on the exact same day as the harvest, no such losses were recorded. From these successful, same-day extractions, it was possible to quantify the amount of extractable fiber in relation to biomass, which proved to be very low, ranging from 2.3% to 7.8% (Table 9).

Table 9. Yields and losses of cardoon stalk biomass.

| Sampling date | Yield DM kg/ha | Extracted fiber g/kg | Fiber yield kg/ha | In field losses kg/ha | Processing losses kg/ha |
|---------------|----------------|----------------------|-------------------|-----------------------|-------------------------|
| 18.7.2025     | 496            | 77.7                 | 39                | 0                     | 418                     |
| 27.8.2025     | 436            | 0                    | 0                 | 393                   | NA                      |
| 05.09.2025    | 389            | 22.8                 | 8.9               | 0                     | 366                     |

## Economic interpretation

The economic viability of cardoon (*Cynara cardunculus*) for fiber production is currently constrained by significant biological risks and market uncertainties. While the crop offers low-input advantages (drought tolerance, minimal fertilization), the potential for harvesting stalks for fiber must be weighed against the established, high-value markets for flowers and seeds (Table 10).

The primary revenue streams for cardoon in the Mediterranean region are well-established:

- Flowers: Market prices range from 25-45 €/kg, representing a high-value, low-volume product.
- Seeds: Sold at 2 €/kg for industrial use.
- Stalks (fiber): Currently, no established market price exists for cardoon stalks in the fiber sector. The FIBSUN project aims to define this value, but preliminary data suggests that both the stalk yields and the extractable fiber yield are low (2.3%-7.8% of dry biomass).

Table 10. Yields and revenues of different cardoon plant parts.

| Plant part | Average yield | Unit  | Price € per unit | Yield €/ha/year |
|------------|---------------|-------|------------------|-----------------|
| Flower     | 12            | kg/ha | 35               | 420             |
| Seed       | 50            | kg/ha | 2                | 100             |
| Stalk      | 440           | kg/ha | TBD              | TBD             |

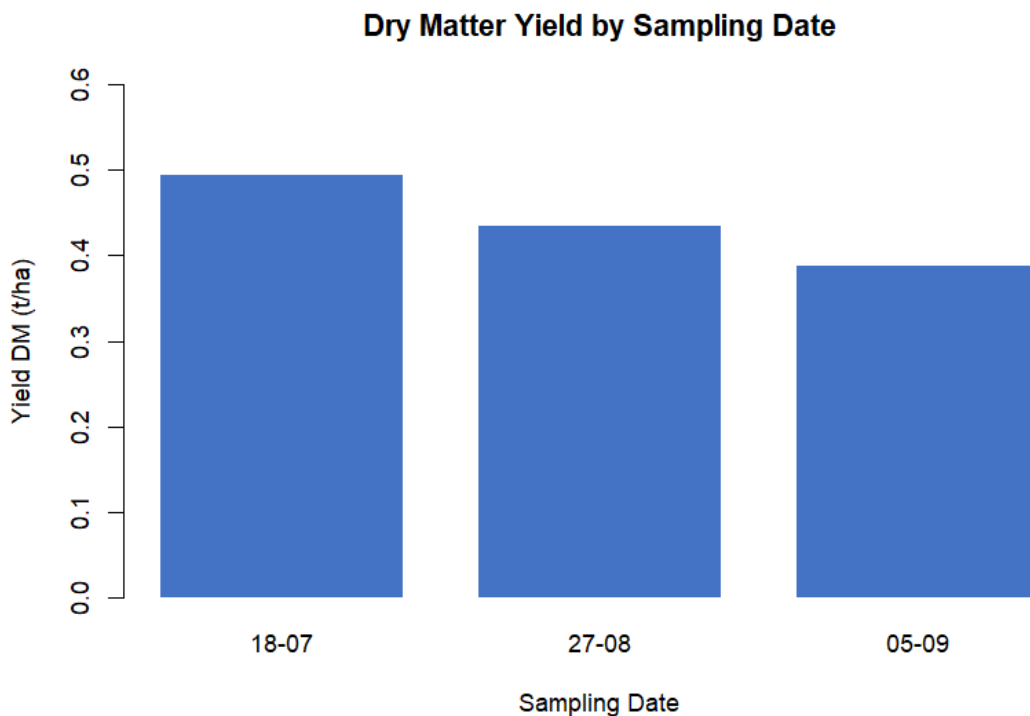


Figure 10. Cardoon stalk yields in 2025 from three harvests, t/ha from three sampling dates. All harvests were conducted at Ourique site.

A critical economic barrier is the high susceptibility of cardoon to pest damage. During the project, one harvest event resulted in up to 90% yield loss due to butterfly larvae infestation. This volatility introduces a significant risk that must be factored into any economic model. Unlike Typha or Phragmites, which showed no pest losses, cardoon requires robust Integrated Pest Management (IPM) strategies to ensure stable production. The timing of fiber extraction (e.g., the 3-day delay that contributed to the infestation) also highlights the need for rapid processing infrastructure to prevent biological losses.

### Viability of stalk harvest

To determine whether harvesting stalks is economically beneficial for the farmer, the marginal revenue generated by the stalks must be compared against the marginal costs incurred by harvesting them.

On the cost side, stalk harvesting at the current site requires manual labour estimated at approximately 147 €/ha (24 man-hours/ha at the 2025 Portuguese minimum agricultural wage of 6.13 €/hour). This figure covers cutting, cleaning, bundling and bagging, but excludes transport to the processing facility and any post-harvest processing costs. Given the low average fiber extraction rate of approximately 5% of dry stalk biomass (ranging from 2.3% to 7.8% across the successful harvests), the cost per kilogram of usable fiber is inherently high even before transport and processing are considered.

On the revenue side, for stalk harvesting to be economically beneficial, the market price per kilogram of extracted fiber must exceed the break-even threshold. Based on the data collected, the average stalk yield is approximately 440 kg DM/ha, yielding an estimated



22 kg/ha of extractable fiber ( $440 \text{ kg/ha} \times 5\%$ ). At a harvesting cost of 147 €/ha, the fiber price would need to exceed 6.70 €/kg just to cover the harvesting labour alone, without accounting for transport, processing, or any overhead costs. When these additional costs are factored in, the effective break-even price rises substantially.

For comparison, if the flower market is available (25-45 €/kg, with an average of approximately 35 €/kg), the farmer generates an estimated 420 €/ha from flowers alone ( $12 \text{ kg/ha} \times 35 \text{ €/kg}$ ) at a harvesting cost of approximately 196 €/ha: a net margin of roughly 224 €/ha from a single, well-established value chain. Given this, a farmer operating both value chains would need to weigh the additional 147 €/ha stalk harvesting cost against an uncertain and currently non-existent fiber market price, with no guarantee of recovering even the labour investment. In the absence of an established market price for cardoon stalk fiber, the economic case for stalk harvesting as a primary revenue stream remains weak.

#### Alternative fiber sources: Cardoon leaves

Given the potential ecological importance of the stalks for insect reproduction, the high risk of pest damage, and the logistical conflict with the primary flower and seed value chain, an alternative approach was investigated. Because the majority of the stalk volume consists of pith (marrow) with fibers only present on the exterior, it was hypothesized that the large basal leaves, which grow much earlier in the season and can be harvested without disrupting the flower and seed production, could serve as an alternative fiber source.

To test this, a harvest of leaves was conducted on 3 March 2026. The material was shipped via same-day express courier, and extraction was attempted immediately upon arrival. However, the mechanical extraction proved unsuccessful. According to the processing facility, when the leaf material was inserted into the machine, it was chopped and ground rather than undergoing the intended scraping process for fiber separation (Figure 11). It is likely that the fibers present in the leaves are either too fragile to withstand the mechanical decortication, or the leaves themselves were too green and possessed an excessively high moisture content for the machinery to process effectively. Consequently, cardoon leaves do not currently present a viable alternative for fiber extraction using standard thermo-mechanical pulping equipment.



Figure 11: Grinded biomass from the leaf fiber extraction attempt. Cardoon leaves do not currently present a viable alternative for fiber extraction using standard thermo-mechanical pulping equipment. Photo: Filipe Soutinho.

### Overall assessment and future outlook

The assessment of cardoon (*Cynara cardunculus*) for fiber production reveals ecological, technical, and economic barriers that currently limit its viability. Ecologically, the stalks serve as a critical habitat for insects, creating a high risk of catastrophic yield loss (up to 90%) unless processing is instantaneous, a logistical hindrance difficult to scale. Technically, alternative biomass fractions like leaves proved unsuitable for mechanical extraction due to fragility and moisture, leaving the risky stalks as the only fiber source. Economically, the low fiber yield (2.3-7.8%) and undefined market price cannot justify the high labor costs, especially when compared to the robust, high-margin returns of established flower and seed markets.

Consequently, while cardoon remains a promising crop for flower and seed production, its use as a primary fiber feedstock is currently premature. Commercial viability depends on resolving the pest-processing issue, developing gentler extraction technologies, and securing a guaranteed fiber market. Until then, the economic recommendation is to prioritize the high-value flower and seed chains, treating stalk biomass as a secondary by-product rather than a primary revenue driver.

### Ecological Implications of Stalk Harvesting

While the economic limitations of cardoon stalk harvesting are significant, the ecological trade-offs provide an equally compelling argument for retaining the stalks in the field. The removal of stalk biomass directly impacts two critical environmental parameters: local biodiversity and soil carbon sequestration.

As observed during the pilot harvests, cardoon stalks serve as potential nesting and hatching habitats for local insect communities, including specific Lepidoptera species. The 90% yield loss caused by butterfly larvae highlights the extent to which these plants

are integrated into the local ecosystem. Harvesting the stalks disrupts these reproductive cycles and removes crucial overwintering habitats. Prioritizing the flower and seed harvests while leaving the stalks standing allows the crop to act as a biodiversity reservoir, supporting pollinator populations and natural pest predators.

Furthermore, retaining stalk biomass is a fundamental practice for advancing regenerative agriculture and carbon farming objectives. Cardoons already contribute to carbon sinks via their deep perennial root system. Allowing the lignocellulosic above-ground biomass to naturally senesce and decompose in the field provides a continuous input of organic matter back into the soil. This organic carbon return is highly beneficial for stimulating soil microbiome health, improving moisture retention, and accelerating the regeneration of marginal, low-input soils.

In conclusion, concentrating exclusively on the flower and seed value chains aligns with both economic rationality and ecological best practices. Leaving the stalks unharvested maximizes the ecosystem services provided by cardoon cultivation, simultaneously protecting vulnerable insect biodiversity and enhancing long-term soil carbon storage.

## 2.4 Industrial hemp

The hemp (*Cannabis sativa* L.) cultivated at the studied site is primarily grown for the production of hemp seeds, which are commonly used for hemp seed oil and food products. In the current production system, only the seeds are harvested. Within the FIBSUN project, the potential use of the remaining plant biomass (stems and fibers) is being explored for the production of hemp fibers, which can be further processed into non-woven insulation materials and composite components for the automotive industry. This approach reflects the increasing interest in multifunctional hemp cultivation, where both seeds and fibers are valorized to improve economic and environmental performance.

The model site used in this project, Bühl site, covers 2.7 hectares, and is located in Waldhegenich, Germany, within a designated nature and landscape conservation area. The land was previously used for maize cultivation and has been dedicated to hemp production after that. The transition from conventional cropping to hemp cultivation contributes to crop diversification and (possibly) improves soil structure and biodiversity in the long term.

Yield data from the Bühl site were limited to the 2024 growing season, as hemp cultivation ceased at this location following that year, and no records were available for 2023. To ensure robust representation of variation, yield data from two additional German cultivation sites, Frankenau and Sandbeiendorf, were integrated into the dataset. Financial estimations are based on the Bühl production site and compared to commonly used business case figures for hemp.

### Site preparation, establishment and maintenance costs



Prior to each growing season, the field is assessed for soil compaction and, if necessary, remediated through tillage operations. On sites with a higher risk of soil erosion, a winter cover crop is established to protect the soil and enhance organic matter content before hemp cultivation. Hemp requires a firm and well-prepared seedbed to ensure optimal soil–seed contact and uniform germination. At the Bühl site, soil preparation is carried out annually and entails an average cost of approximately 270 €, corresponding to about 100 € per hectare.

Following soil preparation, hemp is sown in spring, typically between April and May. As an annual crop, hemp must be resown every year. Sowing operations at the Bühl site generated total costs of approximately 162 €, equivalent to approx. 60 € per hectare. For drought-tolerant hemp, irrigation is applied only when required. There was no need for irrigation during the project. Nutrient supply is ensured through the use of organic fertilizers during the growing season to support crop establishment and growth costing 540 € per field, equivalent to 200 € per hectare. Hemp is generally characterized by rapid early growth and strong competitiveness against weeds, which can reduce the need for herbicides and make it particularly suitable for low-input and organic farming systems.

### Harvesting costs

Harvesting is scheduled approximately 100 to 130 days after sowing, typically between August and September, coinciding with seed maturity. At the Bühl site, harvesting was performed using a combine harvester equipped with a modified Kemper corn deep-cut cutting unit and a specialized chopping device (Fig. 12). This configuration reduces the hemp stem length to approximately 45-60 cm, facilitating subsequent handling. The reported harvesting cost for the 2.7-hectare field was 594 €, equating to 220 €/ha. Due to the high moisture content of the straw (averaging 80% across four samples in 2024), drying and baling are required before transportation and fiber processing. These operations were conducted on-site at the farm. The total cost for drying and baling the field was 270 €, resulting in an additional cost of 100 €/ha. It is important to note that drying and baling represent incremental costs incurred only when the straw is valorized for fiber production. In seed-only production systems, these post-harvest steps are unnecessary, which alters the cost structure.



Figure 12. Industrial hemp harvest in Bühl with a combine harvester equipped with a modified Kemper corn deep-cut cutting unit. Photo: Almut Frank.

### Yield and crop quality

Cultivation conditions using the Finola 2 variety, seed yields are estimated at approximately 800 kg per hectare. For the 2.7-hectare test field, this corresponds to a total production of 2,160 kg of seeds. With an average market value of approximately 1.80 € per kilogram of seeds, hemp seed production represents a viable source of income. If cultivation was optimized for both seed and straw production using a dual-purpose variety, additional revenues of around 150 € per ton of straw could be generated. Straw yield data was acquired from actual harvested yields in the field in 2023 in Frankenau, when the straw yield was reported to be 7.5 t DW/ha and in 2025 in Sandbeiendorf where the straw yield was 2.7 t DW/ha. In Bühl in 2024 the straw yields were measured as 3.7 tons DW per hectare and seed yield as 0.8 t DW/ha. These result in average straw yields of 4.6 t DW/ha 2023-2025, which highlights the significant potential of hemp biomass for fiber-based applications and bio-based material production (Fig. 13). There were no pest/disease-related losses in any of the locations, however, the yields in Sandbeiendorf were reported to have remained lower than usual due to cold and wet conditions in the springtime (during establishment).

In case of hemp straw, 31% of the dry biomass is usable for fibers, 25% for technical fibers, 4% for short fibers and 2 % for super short fibers (Table 11). The remaining dust can be used in energy production or it can be put back in the field as fertilizer/carbon enricher.

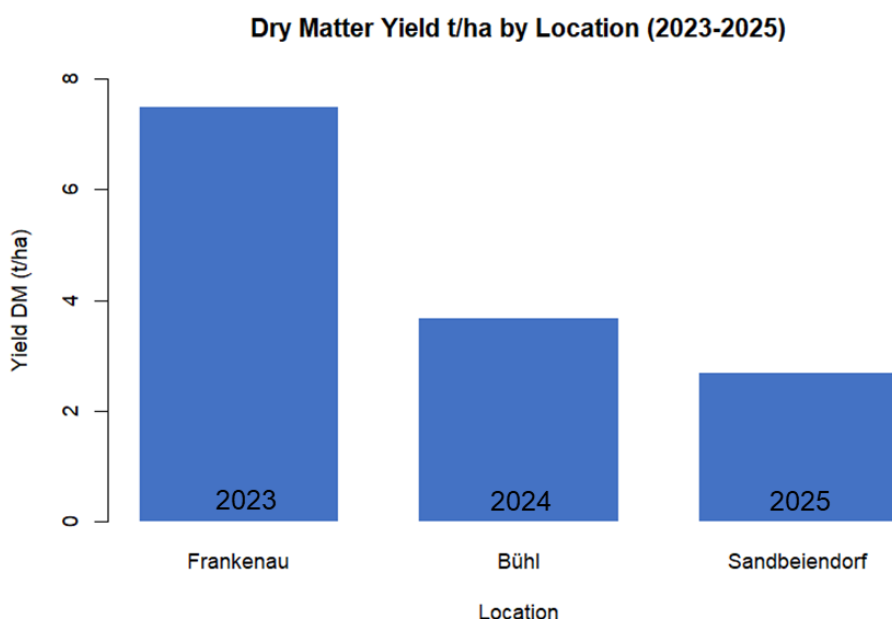


Figure 13. Straw yields t/ha DW 2023-2025 from three locations: Frankenau, Bühl and Sandbeiendorf.

Table 11. Details of straw yield using 2023-2025 average.

| Fraction DM                  | Yield       | Unit        |
|------------------------------|-------------|-------------|
| <b>Total yield</b>           | <b>4.63</b> | <b>t/ha</b> |
| Technical fibers             | 1.16        | t/ha        |
| Short fibers                 | 185         | kg/ha       |
| Super short fibers           | 93.0        | kg/ha       |
| Processing losses            | 3.19        | t/ha        |
| <b>Extracted fiber total</b> | <b>1.44</b> | <b>t/ha</b> |

### Economic performance at the Bühl site

Based on the reported yields of approximately 800 kg of seeds per hectare and an average market price of 1.80 €/kg, the gross revenue from seed production amounts to 1,440 €/ha. When compared to the reported production costs for soil preparation, sowing, fertilization and harvesting (approx. 480€/ha), hemp seed cultivation alone already provides a positive economic margin 960 €/ha under the given conditions (Table 12).

When the remaining biomass (straw) is also utilized, the economic potential of hemp can be significantly improved. Measurements from the field indicate an average straw yield of approximately 4.63 t dry matter per ha. If we use the estimated market value of 150 €/tDM for the straw, it could generate an additional 695 € per hectare in revenue with only approx. 320 €/ha of additional costs. Under such production system, the total revenues could increase to approx. 1,330 €/ha. Even with the added baling and drying costs, using the straw biomass brings 39% increase to the balance margin compared to using the seeds only.

Table 12. Revenues, costs and balance margins in only seed and seed + straw scenario.

| Indicator                    | Seeds Only €/ha | Seeds + Straw (Dual-Use) €/ha |
|------------------------------|-----------------|-------------------------------|
| Revenue (seeds)              | 1,440 €         | 1,440 €                       |
| Revenue (straw)              | 0 €             | 690 €                         |
| Total revenue                | 1,440 €         | 2,130 €                       |
| Base costs                   | 480 €           | 480 €                         |
| Additional processing/diesel | 0 €             | 200 €                         |
| Transport (straw)            | 0 €             | 120 €                         |
| Total costs                  | 480 €           | 800 €                         |
| Net margin                   | 960 €           | 1,330 €                       |
| Increase in margin           | -               | 39%                           |

Overall, the economic assessment highlights that while hemp seed production alone can provide a viable income stream, the valorization of hemp straw and fibers substantially enhances the profitability of the system. Integrating fiber processing into the production chain not only improves economic returns but also supports the development of circular bioeconomy value chains by using the full biomass.

#### Broader industry context: Comparison of different hemp cases in Germany

While the Bühl site demonstrates a highly favorable outcome due to its specific low-input conditions and nature conservation status, broader industry data suggests that standard hemp farming faces tighter margins. A comparative analysis of publicly available German benchmarks (Christen & Klaiss, 2023; Hanffaser Uckermark, 2026; Brandenburg & Thüringen data) reveals a stark contrast between low-input and high-input scenarios (Table 13).

In a low-investment, low-yield scenario (typical of marginal soils without specialized logistics), fibre hemp is often not economically attractive without subsidies. Data indicates a deficit of approximately -265 €/ha before land costs and -363 €/ha including rent. In these cases, the crop only approaches breakeven when Common Agricultural Policy (CAP) payments are included. The primary cost drivers in these scenarios are soil preparation and harvesting, which can be significantly higher than at the Bühl site.

Conversely, a high-investment, high-yield scenario (targeting 10 t/ha straw yield) demonstrates clear commercial viability. With contracted prices of roughly 190 €/t for hemp straw, revenue can reach 1,900 €/ha against costs of 1,370 €/ha, leaving a gross margin of +530 €/ha before rent. This model relies heavily on quality (meeting strict retting classes, stem thickness, and moisture standards), contracts (securing a guaranteed off-take agreement with a processor, as spot markets for hemp are poorly developed) and logistics (stationing harvesting equipment close to the site to minimize transport and operating costs).

Table 13. Main comparison table (source: Christen & Klaiss, 2023; Hanffaser Uckermark, 2026a,b; Praxis-Agrar Bundesanstalt für Landwirtschaft und Ernährung, 2025; Thüringer Landesanstalt für Landwirtschaft (TLL), 2005; Branchenverband Cannabiswirtschaft, 2025): cost and revenues €/ha/year.

| Cost / revenue item                                          | Low investment – low yield | High investment – high yield |
|--------------------------------------------------------------|----------------------------|------------------------------|
| Soil management + sowing + machinery/fuel/labour/management* | 364                        | 175**                        |
| Seed                                                         | 132                        | 350                          |
| Fertilizer                                                   | 65                         | 200                          |
| Pesticides / plant protection                                | 0                          | 0                            |
| Irrigation (baseline)***                                     | 0                          | 0                            |
| Harvest / mowing contractor                                  | 129                        | 100                          |
| Baling / pressing                                            | 104                        | 310                          |
| Transport / storage / handling                               | 71                         | 150                          |
| Stubble cultivation after harvest                            | included in first row      | 30                           |
| Other overhead / insurance / general farm cost               | 65                         | 40                           |
| Stone picking / field hygiene                                | included in first row      | 15                           |
| <b>Total cost before land cost</b>                           | <b>930</b>                 | <b>1,370</b>                 |
| Land cost / rent (where published)                           | 98                         | not published in source      |
| <b>Total cost incl. published land cost</b>                  | <b>1,028</b>               | <b>1,370 + local rent</b>    |
| <b>Fibre-hemp revenue</b>                                    | <b>665</b>                 | <b>1,900</b>                 |
| <b>Result before land cost</b>                               | <b>-265</b>                | <b>+530</b>                  |
| <b>Result incl. published land cost</b>                      | <b>-363</b>                | <b>+530 - local rent</b>     |

\* In the low-input Thüringen benchmark, this row is an aggregate derived from the published full-cost table and covers the non-separated field-operation block around ploughing, seedbed preparation, drilling, fuel, machinery, labour, management, and associated logistics (Thüringer Landesanstalt für Landwirtschaft 2005).

\*\* High-input row = soil preparation (€90/ha) + sowing (€70/ha) + stubble-related field work share not already separated here. The high-input source publishes several field-work items individually (Hanffaser Uckermark 2026b)

\*\*\* We set irrigation to 0 in the baseline budgets because irrigation is not standard practice for representative German fibre-hemp production; however, if establishment drought makes irrigation necessary, one 30 mm irrigation pass can add roughly €227–377/ha, depending on system and distance (Praxis-Agrar Bundesanstalt für Landwirtschaft und Ernährung 2025).



Interestingly, dual-purpose production (harvesting both seeds and straw) in these standard benchmarks shows slightly lower margins than fibre-only production in some contexts (Table 14). While seed revenue adds value, the straw yield and revenue often drop by approximately 30% due to the harvest timing compromise, and the extra handling costs for seeds can erode the margin. For example, in low-productive soil scenarios (45 Bodempunkte), the gross margin for fibre-only is +530 €/ha, whereas fibre + seed drops to +455 €/ha.

Table 14: Comparison of revenue, costs and gross margin of fibre production and dual-purpose hemp production for low productive soils (45 BP – Bodempunkte).

| Scenario (45 BP) | Revenue €/ha | Cost €/ha | Gross margin €/ha | Source year |
|------------------|--------------|-----------|-------------------|-------------|
| Fibre-only       | 1,900        | 1,370     | +530              | 2026        |
| Fibre + seed     | 1,870        | 1,415     | +455              | 2026        |

### Conditions for commercial viability

Comparing the results from the Bühl pilot site with wider German industry data gives useful insights into how scalable hemp fiber production really is. The Bühl site achieved a strong profit margin of +1,330 €/ha mainly because of its low production costs. It required very little soil preparation, no irrigation, and also generated extra income through seed sales. This shows that hemp can be especially profitable on marginal or conservation land, where farming inputs and costs are naturally lower and both fiber and seeds can be sold.

At the same time, industry data shows that high yields alone do not guarantee profitability in standard commercial farming. Even in more intensive production systems, success depends heavily on reliable processor contracts and efficient logistics. Because spot markets for hemp are still poorly developed, farmers need secured purchase agreements to achieve stable and viable product prices. Without guaranteed buyers, producers face significant risks from market volatility and uncertain demand.

The data also suggests that dual-purpose harvesting is not always the best option. If harvesting seeds reduces the quality or quantity of the straw, profits may end up lower than with a crop grown only for fiber. However, harvesting seeds for food consumption can still be an attractive way to diversify farm income, especially if demand for hemp food products continues to grow and markets are able to absorb larger production volumes.

As a result, commercial hemp production requires a careful strategy. Hemp can be economically viable when several conditions are met. Site-related costs should be kept as low as possible, similar to the Bühl case. Harvesting equipment should be located close to production sites and operated at low cost to avoid expensive logistics. Farmers should also secure processor contracts early in the season to guarantee prices and quality requirements. In addition, the trade-off between seed revenue and possible reductions in straw yield or quality must be carefully evaluated, since dedicated fiber production may be more profitable in some high-yield situations.

Overall, hemp seed production provides a stable source of income, but using the straw as an additional product can significantly improve profitability when high yields, strong quality control, low operating costs, and secure markets are all achieved together. The Bühl site demonstrates that low-input, dual-purpose hemp systems can work

successfully, while broader industry data highlights the practical conditions needed for larger-scale commercial adoption.

## 2.5 Wood on contaminated soil

For FIBSUN the wood was collected from a contaminated site in Pont-de-Claix, France, where Poplar (*Populus sp.*), willow (*Salix sp.*), and black locust (*Robinia pseudoacacia*) established themselves spontaneously. In FIBSUN we monitored the qualities of trees grown on contaminated soils and their abilities to remove contaminants from the soil while improving the overall soil health and biodiversity. The wood biomass is used as a raw material for bioconcrete. These trees can also be planted in more commercial setting on contaminated soil. Here we explore the costs and profits of a poplar plantation in France, assuming the wood growing on contaminated soils can be applied on a commercial level.

### Site preparation, establishment and maintenance costs

Before the establishment of a plantation, the land must be prepared through intensive soil treatment. In the year preceding planting (year -1), heavy grinding is carried out to remove existing vegetation and improve soil structure. The operation is performed using heavy grinding machinery and represents a significant initial intervention, with an average cost of 1000 € per hectare (ranging from 600 to 1400).

In the planting year (year 0), several activities are implemented. First, seedlings are acquired at a density of 204 stems per hectare, with an average cost of 1200 per hectare (minimum 1000, maximum 1400). To ensure successful establishment, wildlife protection measures are installed for the same number of stems, with an average cost of 200 per hectare (range 160-240). Planting operations are then carried out, also based on 204 stems per hectare, with an average cost of 1100 per hectare (range 900-1300). These combined interventions ensure proper plantation establishment and early-stage survival of the trees.

Following planting, the plantation requires regular maintenance to support growth and reduce competition from weeds and other environmental pressures. Maintenance activities are conducted in years 1, 2, 4, and 6. Each maintenance intervention has an average cost of 400€ per hectare, with a minimum of 300€ and a maximum of 500€. These activities typically include weed control, soil management, replacement of failed plants if necessary, and general monitoring of plantation health.

In addition to maintenance, pruning operations are carried out to improve tree form, timber quality, and long-term productivity. The first pruning takes place in year 2, with an average cost of 450 per hectare (range 380-520). The second pruning is conducted in year 5, with an average cost of 650 per hectare (range 520-780). The third pruning occurs in year 8, with an average cost of 900 per hectare (range 700-1100). These progressive pruning interventions reflect the increasing complexity and intensity of operations as trees grow.

Overall, the total average cost of all interventions over the plantation cycle amounts to 7100 € per hectare, with a minimum estimated cost of 5460 and a maximum of 8740 €/ha. This cost structure highlights the importance of both initial establishment activities

and long-term management practices in ensuring the successful development of the plantation.

The costs of establishing and maintaining a poplar plantation are listed below in Table 15.

Table 15. Poplar plantation costs in France (in €/ha) resumed in the following table by steps.

| Intervention                       | Year | Average     | Min         | Max         |
|------------------------------------|------|-------------|-------------|-------------|
| Land preparation: Heavy grinding   | -1   | 1000        | 600         | 1400        |
| Seedlings (204 stems/ha)           | 0    | 1200        | 1000        | 1400        |
| Wildlife protection (204 stems/ha) | 0    | 200         | 160         | 240         |
| Planting (204 stems/ha)            | 0    | 1100        | 900         | 1300        |
| Maintenance 1                      | 1    | 400         | 300         | 500         |
| Maintenance 2                      | 2    | 400         | 300         | 500         |
| Maintenance 3                      | 4    | 400         | 300         | 500         |
| Maintenance 4                      | 6    | 400         | 300         | 500         |
| Pruning 1                          | 2    | 450         | 380         | 520         |
| Pruning 2                          | 5    | 650         | 520         | 780         |
| Pruning 3                          | 8    | 900         | 700         | 1100        |
| <b>Total</b>                       |      | <b>7100</b> | <b>5460</b> | <b>8740</b> |

Unlike plywood, veneer production or light wooden crate, which require high-quality round wood, straight-grained with diameter specifications, the production of wood particles for wood-concrete does not impose such constraints on raw material quality. The chipping and grinding process homogenises the wood regardless of its initial form, meaning that crooked stems, forked logs, small-diameter wood, or timber with knots and defects could be suitable for bioconcrete applications.

This opens up a broader and more flexible sourcing base: forest residues, thinning wood, low-grade logs rejected by the sawmill or plywood industry, and industrial by-products can all be valorised. In the context of poplar supply, this is particularly relevant, as poplar plantations naturally produce a proportion of stems that do not meet the quality thresholds required by the peeling industry. Rather than being downgraded to pulpwood or left with limited commercial value, these lower-grade stems become a fully viable, and cost-competitive, feedstock for particles production.

### Harvesting costs

Harvest is expected to take place between 14 and 22 years after planting, with an average rotation period of approximately 18 years. The trees harvested in Pont-de-Claix were 9 years old, due to the project's needs. As the site closed in 2014, we had no opportunities to collect trees older than 9 years old. In Pont-de-Claix, the harvest for the test biomass was conducted manually using a chainsaw. In a commercial plantation setting, the trees are harvested using a tracked excavator fitted with a forestry grapple-saw (or felling head, Fig. 14). In addition to this, a forwarder/skidder is needed to carry the logs from the field to the landing. After this, the logs need to be loaded onto a timber truck and transported to the further processing location.



While the pilot harvest at Pont-de-Claix was conducted manually, commercial poplar plantations in France typically utilize fully mechanized systems. Standard harvesting costs for poplar in France range between 45 € and 75 € per cubic meter (m<sup>3</sup>) for the complete operation (felling, delimbing, bucking, and forwarding to the roadside). For a standard yield of 200-250 m<sup>3</sup>/ha, this translates to a total harvesting cost between 9,000 € and 18,750 € per hectare. These figures assume a rotation age of 15-20 years and accessible terrain. The manual method used at Pont-de-Claix, while necessary for the pilot, is significantly more labor-intensive and would not be economically viable at a commercial scale.



Figure 14. Manual harvesting in Point-de-Claix (left) and plantation harvesting of poplar with an excavator with grapple saw in Primarette (Isère) (right). Photos: Edern Philippot.

### Yields, revenues and crop quality

We calculated the yields and revenues using the more typical 18 years of growth. A stepwise mass balance was performed using experimentally measured and literature-based yields for each transformation stage. Starting from 100 units of initial biomass, the final yield of target particles (3–7 mm) ranges from 50.4% to 58.1%, depending on process conditions.

Expected yields of collectible wood are estimated between 200 and 250 m<sup>3</sup> per hectare. This range reflects potential variability in productivity due to factors such as soil quality, climate conditions, stand density, and management intensity. A substantial proportion, approx. 89% of the harvested wood material is usable for bioconcrete (Table 16). Small fraction (< 2%) of the material is rejected due to too small size (<5 mm) and another fraction (< 7%) is rejected to too large size (> 3 cm).

From this collected wood, several yield factors must be taken into account when assessing the transformation process from poplar harvesting to the production of wood particles. At each stage, material losses and quality variations can significantly impact the overall efficiency.

Considered steps for yields figures include: harvesting, debarking, chipping into wood chips, grinding into particles, and finally screening (Figure 15). Each of these steps contributes to the cumulative yield, making it essential to evaluate them individually to obtain an accurate understanding of the overall process performance.

The yields presented here are derived either from poplar plantation management data (provided by FCBA) for harvesting operations, or from measurements directly carried out at FCBA facilities for debarking, wood chipping, grinding, and sieving processes. Equipment details are available in deliverable 2.2.



Figure 15. Processing steps for wood: harvesting, debarking, splitting, chipping into wood chips, grinding into particles, and screening. Photos: Edern Philippot.

#### Harvesting losses (initial biomass losses)

Typical harvesting losses in poplar plantations generally range from 5 to 10% of the standing volume. These losses mainly correspond to parts of the tree that are not harvested or not valorized, such as branches and the crown (top of the tree), as well as defective sections removed during processing (e.g., rot, curvature, or damage), and small-diameter wood that does not meet industrial specifications. (see figure 1 illustrating harvested wood logs and the small branches counting as losses left on the ground after harvesting.)

#### Debarking losses (removing bark and reducing usable mass)

Bark represent 10 to 12% of the collected wood.

No losses were measured during the logs splitting step. At large scale, splitting losses are minimal and mainly consist of small wood fragments, small chips, and defective portions removed during processing. Therefore, splitting losses can reasonably be estimated from 2 to 5% of the total mass.

#### Chipping losses (producing material suitable for further grinding and involving an initial sorting of the resulting wood chips)

Chipping trials were conducted on poplar logs of 80 to 100 cm length. Produced chips exits onto double deck oscillating sieves with openings of 5 mm for lower deck and 3 cm for upper deck. The fraction passing between the two sieves is considered as accepted chips, the other two fractions are considered rejected. Therefore, chips sizes fractions are classified into three groups: rejected small chips (< 5 mm), accepted intermediate chips, and rejected big chips (> 3 cm). The following table shows the yields obtained on

the different fractions in two chipping trials involving batches of logs with a total weighing of 26.5 kg and 24 kg at a humidity rate of 45%.

Table 16. Fiber yields and processing losses.

| Wet log mass (kg) | Rejected small chips (<5mm) | Accepted intermediate chips (between 5 and 3 cm) | Rejected big chips (>3cm) |
|-------------------|-----------------------------|--------------------------------------------------|---------------------------|
| 26,5              | 1,93%                       | 90,57%                                           | 6,63%                     |
| 24                | 1,76%                       | 87,50%                                           | 7,73%                     |

The yields of the accepted fraction reached 90.6% and 87.5%. These values indicate a high overall process performance, consistent with the production of quality wood chips. To optimize these yields, rejected big chips fraction can be reintroduced into the grinding/sieving process.

Grinding and sieving losses (wood material is generated to its final dimensions and particles are separated by size and rejects removed)

The accepted chips produced following the chipping stage are fed into another knife mill (details of the equipment and operations are provided in deliverable D2.2). The resulting particles are then screened in two stages (using 3 mm and 7 mm mesh sizes), yielding three fractions (less than 3 mm, between 3 and 7 mm, and greater than 7 mm). The fraction selected for use in wood concrete is the fraction between 3 and 7 mm.

To measure losses during grinding and sieving, measurements were performed on five samples of unsorted poplar particles. For each test, the initial mass of the wood samples was approximately 500 g at a humidity rate of 11%. The following table shows the mean and standard deviation of the mass percentages obtained with each fraction (Table 17).

Table 17. Losses during sieving.

|                        | % < 3 mm | 3 mm < % < 7 mm | % > 7 mm |
|------------------------|----------|-----------------|----------|
| Mean (%)               | 19.6     | 76.6            | 3.8      |
| Standard deviation (%) | 1.2      | 1.3             | 0.3      |

The particle size distribution is largely dominated by the 3–7 mm fraction, which represents approximately 77–79% of the total mass and corresponds to the main target product. The proportion of fines (<3 mm) ranges from about 18% to 21%, which is significant and may reflect either the intrinsic fragility of the raw material or a relatively intense fragmentation during processing. The coarse fraction (>7 mm) remains limited, at around 3–4%, indicating good upstream size control and an efficient comminution stage. Overall, the results are highly consistent across replicates, with only minor variability, mainly observed in the fines fraction.

Due to the equipment available for this study, it was necessary to include an intermediate wood chipping step to process the logs (Table 18). However, for this application and at an industrial scale, this step would most likely be eliminated, allowing a direct conversion from logs to particles in order to simplify the process and reduce handling and maintenance costs. Wood chipping step remains widely used in some industrial

processes, as it helps to homogenize the feedstock, improve control over the final particle size distribution, and enhance overall process stability. As a result, many industries, particularly in the panel and bioenergy sectors, still rely on this intermediate step.

Table 18. A summary of the different materials yields across the different transformation steps to turn a poplar tree into ready to use particles for wood concrete applications.

| Process step                                                          | Main loss / transformation                                 | Step yield (%)                | Cumulative yield (%) | Cumulative losses (%) |
|-----------------------------------------------------------------------|------------------------------------------------------------|-------------------------------|----------------------|-----------------------|
| <b>Harvesting</b>                                                     | Unharvested biomass (branches, crown, defects, small wood) | 90 – 95                       | 90 – 95              | 5 – 10                |
| <b>Debarking</b>                                                      | Bark removal                                               | 88 – 90<br>(after harvesting) | 79 – 86              | 14 – 21               |
| <b>Splitting / primary processing</b>                                 | Small fragments, defects (industrial estimate)             | 95 – 98<br>(after debarking)  | 75 – 84              | 16 – 25               |
| <b>Chipping (accepted fraction)</b>                                   | Oversized + fines rejection                                | 88 – 91<br>(after splitting)  | 66 – 76              | 24 – 34               |
| <b>Grinding &amp; sieving (final product fraction between 3–7 mm)</b> | Fines + coarse particles                                   | 76 – 79<br>(after chipping)   | <b>50 – 60</b>       | <b>40 – 50</b>        |

Across all stages, cumulative yield is strongly influenced by early biomass losses (harvesting and debarking) and by fragmentation behavior during size reduction. While chipping and grinding are relatively efficient, the system generates unavoidable fines, and overall performance depends on the balance between product quality and material losses.

The overall process yields can be improved by reintroducing certain oversized fractions or branches, back into the transformation chain. In particular, oversized chips generated during chipping, as well as coarse fractions obtained after screening, can be recycled into the size-reduction stages (grinding and/or rechipping). This recycling strategy helps to reduce the loss of potentially usable material and increases the overall conversion rate into particles that meet final specifications. Recirculation must be optimized to avoid potential degradation of particle quality.

Timber selling prices are estimated to range between 60 and 80 €/m<sup>3</sup>. This gives a range between 12,000 and 20,000 € per harvest. The revenues depend on how fast the trees grow. Assuming they are harvested after 18 years this gives a range of 666-1,111 € per hectare.

### Forestry subsidies

On top of the direct revenues from selling the biomass, in France, there is a possibility to receive forestry subsidies. These are often decentralized and coordinated at the regional level, even though they are framed by national policy and European funding instruments. Most financial support schemes rely on the EU Common Agricultural Policy



(CAP), particularly the European Agricultural Fund for Rural Development (EAFRD), and are implemented regionally through Rural Development Programmes managed by Regional Councils in coordination with state services. Subsidies are allocated by several public bodies depending on the type of project: Regional Councils (which manage EAFRD envelopes), the State through regional directorates such as DRAAF, public forest agencies like the National Forests Office (ONF) for public forests, technical or advisory organizations such as the Regional Forest Property Centres (CRPF) for private owners or from Ecological transition Agency (ADEME) Funding intensity typically ranges from about 30% to 80% of eligible investment costs depending on the scheme, project objectives (reforestation, adaptation to climate change, forest roads, biodiversity, risk prevention), and the applicant profile. Higher co-funding rates are often granted to collective projects, young forest owners, or actions linked to environmental resilience. Eligible beneficiaries generally include private forest owners, forest management groups, cooperatives, municipalities and other public forest managers, and in some cases companies operating in the forestry and wood value chain.

Taking the example of the Auvergne-Rhône-Alpes (AURA) region, subsidies are provided by the Regional Council in coordination with state services like the DRAAF, as well as technical bodies such as the Regional Forest Property Centre (CRPF). Funding typically covers from 40 to 60% of eligible costs, sometimes higher for collective, environmental, or agroforestry projects, and is available to private forest owners, cooperatives, municipalities, and public land managers. For a poplar plantation project in AURA: Expected subsidies from EAFRD and Region can be estimated around 50% and a support of 10 to 20% could be also expected from environmental and agroforestry actors. For a planting cost between €3,000-€6,000 per hectare. Typical remaining cost could be €1,500-€3,000 per hectare, depending on project design.

### Cleaning contaminated soil

What is important to take into account in our economic calculation is the cost of cleaning contaminated soil. Cleaning contaminated industrial soil can be very costly, particularly when conventional remediation methods such as excavation and off-site treatment are used. In France and elsewhere in Europe, the cost of soil remediation typically depends on the type and concentration of pollutants, the volume of affected soil, and the treatment method selected. Excavation and disposal, which involve removing contaminated soil and transporting it to specialized treatment or landfill facilities, generally range from about 120 to 800 € per tonne, equivalent to roughly 150 to more than 1,000 € per cubic meter depending on soil density and contamination complexity. For large sites, these costs can quickly reach hundreds of thousands to several million euros per hectare, especially when pollutants such as heavy metals, solvents, or persistent organic compounds require advanced treatment. Less intensive in-situ remediation methods, such as biological treatment or soil vapor extraction, can reduce costs to approximately 80-150 € per cubic meter, but they typically require longer treatment periods and careful monitoring. As a result, the high financial burden of conventional remediation has led to increasing interest in alternative approaches, such as phytoremediation using tree plantations, which can significantly reduce costs while restoring soil function over longer timeframes.

To support decision-making in soil remediation projects, several tools have been developed to guide the selection of appropriate techniques, notably SelecDEPOL, a



decision-support tool designed by the French Agency for Ecological Transition (ADEME) in collaboration with the French Geological and Mining Research Bureau (BRGM). This interactive tool enables the pre-selection of remediation and risk management solutions based on site-specific characteristics such as contaminant type, depth of pollution, and geological and hydrogeological conditions. It provides detailed technical sheets describing each method, including applicability ranges, maturity level, implementation constraints, as well as indicative costs, advantages, and limitations.

### Economic interpretation

The economic viability of poplar plantations on contaminated soil in France has a unique cost-benefit structure: high initial establishment costs and moderate timber revenues are offset by significant avoided costs associated with conventional soil remediation and potential public subsidies.

**High management/maintenance option:** Establishing a poplar plantation on contaminated land requires a substantial upfront investment. The total cost for site preparation, planting, and maintenance over the first 8 years averages 7,100 €/ha (range: 5,460-8,740 €/ha). This includes intensive land preparation (heavy grinding), seedling acquisition, wildlife protection, and three rounds of pruning to ensure timber quality.

Unlike conventional agriculture, the return on this investment is delayed, with the first harvest occurring only after 14-22 years (average 18 years). However, the cost structure is heavily front-loaded. Once the canopy closes (post-year 6), maintenance costs drop significantly, and the primary recurring expenses are limited to the final harvest operations.

While the pilot harvest at Pont-de-Claix was conducted manually, commercial viability relies on mechanization. Based on French forestry benchmarks, the cost for a fully mechanized harvest (felling, forwarding, loading) ranges from 45 to 75 €/m<sup>3</sup>.

- Estimated harvest cost: For a yield of 200-250 m<sup>3</sup>/ha, total harvest costs range from 9,000 € to 18,750 €/ha.
- Timing: These costs are incurred only once at the end of the rotation (Year 18).

Revenue generated from the sale of timber suitable for bioconcrete production:

- Yield: 200-250 m<sup>3</sup>/ha (18-year rotation).
- Usable fraction: approx. 89% of the volume is accepted for bioconcrete; approx. 11% is rejected due to size constraints.
- Market Price: Estimated at 60-80 €/m<sup>3</sup>.
- Gross Revenue: 12,000 € to 20,000 €/ha per harvest.
- Annualized Revenue: Over an 18-year cycle, this equates to approximately 666–1,111 €/ha/year.

On a purely cash-flow basis (revenue minus establishment + harvest costs), the operation appears to run a deficit. The total costs (7,100 € establishment + approx. 14,000 € avg harvest) exceed the total revenue (approx. 16,000 € avg) unless subsidies and avoided remediation costs are factored in.

The economic models become (more) viable when two additional factors are considered:

- Public subsidies: In regions like Auvergne-Rhône-Alpes, poplar plantations on marginal or contaminated lands are eligible for significant public support.

- Funding Sources: EAFRD, Regional Councils, DRAAF, ADEME.
  - Coverage: Typically 40-60% of eligible establishment costs, potentially rising to 70-80% for environmental projects.
  - Impact: For an establishment cost of 3,000-6,000 €/ha (eligible portion), subsidies could reduce the net private investment by 1,500-3,000 €/ha. This effectively lowers the break-even threshold.
- Avoided remediation costs: The most significant economic driver for this specific use case is the avoidance of conventional soil cleanup costs.
    - Conventional remediation: Excavation and disposal of contaminated soil cost 150-1,000+ €/m<sup>3</sup>. For a standard contamination depth, this can easily exceed 100,000 €/ha.
    - Phytoremediation value: By using poplar trees to stabilize and extract contaminants, the landowner avoids these massive excavation costs. Even if the timber revenue barely covers the plantation costs, the net economic benefit is the difference between the cost of the plantation and the cost of excavation.
      - Example: If excavation costs 200,000 €/ha and the poplar plantation costs 25,000 €/ha (total lifecycle), the net value generated is 175,000 €/ha in avoided liabilities.

Poplar cultivation on contaminated soil in France is not economically viable as a standalone timber production system under current market prices, as the long-term revenue does not fully cover the high establishment and harvest costs. However, it becomes highly viable as a remediation strategy. When viewed as a service that replaces expensive industrial soil cleanup, the model generates substantial positive value. The combination of subsidies covering 40-60% of establishment costs, and avoided remediation costs (saving >100,000 €/ha), creates a robust business case for landowners and municipalities. The biomass revenue serves as a secondary income stream that improves the overall return on investment, transforming a liability (contaminated land) into a productive asset.

Future commercial scaling should focus on securing "remediation contracts" with municipalities or industrial polluters who are liable for cleanup costs, rather than relying solely on timber market fluctuations.

### 3. Integration

Here we synthesize the agronomic and economic findings across the five primary production systems investigated in the FIBSUN project: cattail, reed, cardoon, hemp, and wood on contaminated soil. While each crop possesses unique biological characteristics and site requirements, the economic analysis reveals common drivers of viability and shared challenges that must be addressed for successful upscaling.

#### 3.1 Economic overview

The economic performance of the five crops varies significantly based on the chosen business model and the specific market context. Table 17 below summarizes the key economic indicators for the most viable scenario identified for each species, highlighting the stark differences in cost structures and revenue potential.

Table 17. Summary of economic performance across FIBSUN species (€/ha/year).



| Indicator           | Cattail (Optimal)                       | Reed (Optimal)                        | Cardoon (Projected)            | Hemp (Dual-Use Optimal)  | Wood (Phytoremediation)           |
|---------------------|-----------------------------------------|---------------------------------------|--------------------------------|--------------------------|-----------------------------------|
| Primary value chain | Biorefinery (fiber + flowers + protein) | Mixed stream (thatching + insulation) | Fiber (stalks) + seeds/flowers | Dual-use (seeds + straw) | Bioconcrete + remediation service |
| Establishment cost  | Low-high* (1,000–20,000 €)              | Very low (natural)                    | Low (perennial)                | Medium (annual)          | Very high (7,100 €)               |
| Annual op. costs    | Medium (8,800–26,600 €)                 | Low (2,000 €)                         | Low (est. ~300 €)              | Medium (800 €)           | Low (post-year 6)                 |
| Total revenue       | ~32,300 €                               | ~10,300 €                             | ~520 €**                       | ~2,130 €                 | ~16,000 € (per 18 yrs)            |
| Net balance         | 5,700 €                                 | 8,300 €                               | ~220 €                         | 1,330 €                  | +175,000 € (avoided cost)         |
| Viability Status    | Highly viable (with tech)               | Highly viable (with sorting)          | Uncertain (market risk)        | Viable (seed-driven)     | Viable (service-driven)           |
| Key risk factor     | Flower market volatility                | Transport distance                    | Pest outbreaks (90% loss)      | Straw logistics cost     | Long rotation (18 yrs)            |
| Subsidy dependence  | High (carbon credits)                   | None (Finland)                        | None                           | Low                      | High (establishment)              |

\*Cattail costs range from 1,000 €/ha (sowing on wet land) to >20,000 €/ha (heavy engineering).

\*\*Cardoon stalks still don't have an established market value to be considered

## 3.2 Recurring themes and critical success factors

Across all five species, several critical factors emerged as decisive for economic viability, transcending individual crop biology to point to systemic requirements for the bioeconomy.

The most prevalent challenge identified is the logistics, as transport and drying consistently represent the largest operational cost drivers, often exceeding the cost of harvesting itself. For cattail and hemp, the high moisture content of the biomass necessitates either expensive artificial drying or volume-reduction technologies such as extrusion or field pressing; without these interventions, transport costs render the biomass economically unviable. Similarly, reed viability collapses if transport distances exceed moderate ranges. The clear lesson is that proximity to the processor is non-negotiable, and successful models require localized processing hubs or field-level pre-treatment to reduce transport volume.

Closely linked to logistics is the absolute necessity of diversification of production. Relying on a single revenue stream, such as fiber-only, resulted in deficits or marginal profits in almost all cases. Viability was achieved through product diversification, where farmers capture value from every fraction of the biomass. Cattail succeeds by combining

fiber with flowers and protein; reed by sorting into high-value thatching bundles and insulation fiber; hemp by utilizing both seeds and straw; and wood by treating the crop as a remediation service alongside timber production.

Furthermore, the role of subsidies and ecosystem services cannot be overstated. In the absence of high market prices for biomass, policy instruments often bridge the gap to profitability. For cattail, carbon credits and water storage payments were essential to reach the viability threshold, while for wood, the entire business case relies on avoided costs and establishment subsidies. In contrast, the lack of subsidies in Finland meant that reed viability depended entirely on accessing high-value niche markets like thatching. This indicates that economic models must integrate ecosystem service payments as a core revenue stream rather than an optional bonus.

Finally, biological risks and stability vary drastically between crops. Cattail and reed demonstrated exceptional resilience with zero pest or disease losses over the monitoring period, offering a stable supply. Conversely, cardoon suffered a catastrophic 90% yield loss due to pests, highlighting the critical need for Integrated Pest Management before commercial scaling. Hemp showed good resilience but remains sensitive to weather conditions. This divergence suggests that crop selection must carefully consider biological risk profiles

### 3.3 Hidden costs and overlooked factors

There are some hidden costs that might not be apparent, but can significantly impact the result.

First, sorting and grading labor emerged as a major cost driver. In the optimal reed scenario, the ability to sort biomass into high-value thatching bundles versus low-value insulation fiber added significant labor costs, without which revenue would drop by approximately 30%. Similarly, in cattail, flower harvesting requires roughly 207 man-hours per hectare, creating a major barrier to scaling unless this process can be mechanized.

Second, we focused primarily on variable costs such as fuel, labor and seeds, excluding the infrastructure and machinery capital required for specialized equipment. For new farmers, the cost of acquiring wetland mowers, extruders, or modified combines represents a barrier to entry. However, in practice, this barrier is often mitigated by the availability of custom hiring services. In the case of cattail, for instance, farmers typically do not purchase expensive wetland harvesters outright; instead, they order the mowing and harvesting service from specialized contractors who own the machinery. This "service-based" model allows farmers to access advanced technology without the heavy upfront capital investment, converting a fixed cost into a manageable variable cost. While this does not eliminate the cost of the service itself, it significantly lowers the threshold for entry, making it easier for farmers to adopt these novel crops without bearing the full risk of machinery ownership.

Third, processing losses significantly reduce the gap between field yield and final revenue. Cattail loses approximately 15% of biomass during fiber extraction, reed loses 14% during pulping, hemp loses roughly 69% if only long fibers are sold, and wood suffers a cumulative 40-50% loss from harvest to final particle size. This underscores that field yield is not synonymous with revenue, and the conversion efficiency of the processing chain is a critical economic variable.



Lastly, market immaturity poses a fundamental risk. For cardoon, there is no established market price for stalks, and for cattail, the markets for flowers and protein are still at the pilot scale. This creates a "chicken-and-egg" scenario where farmers cannot invest without a guaranteed buyer, making current economic viability conditional on the future development of downstream markets.

### 3.4 Recommendations for upscaling

Several strategic recommendations are proposed, aiming to scale paludiculture and bio-based fiber production.

To mitigate transport costs, it is imperative to develop regional processing hubs where facilities such as biorefineries and insulation plants are located within a 30-50 km radius of production sites. Simultaneously, investment in pre-treatment technology is essential. Technologies like field extrusion for cattail and field retting for hemp are critical to reduce biomass volume and moisture before transport.

Farmers should be encouraged to adopt integrated business models that utilize multi-product strategies, such as combining seeds with straw or fiber with flowers, to hedge against market volatility. For crops like wood and cattail, business models should be structured around environmental services such as remediation and carbon sequestration rather than relying solely on commodity sales. Finally, for crops like cardoon, robust Integrated Pest Management strategies must be developed and funded before commercial expansion to prevent catastrophic yield losses.

### 3.5 Conclusion

The FIBSUN project demonstrates that sustainable primary production for bio-based fibers is economically feasible, but it is not a one-size-fits-all solution. Reed and hemp offer the most immediate, low-risk pathways for farmers, provided logistics are optimized. Cattail offers the highest potential returns but requires technological innovation and market development. Wood offers a unique solution for contaminated land, transforming an environmental liability into an asset through phytoremediation, while cardoon remains a high-risk candidate pending market definition and pest control solutions.

Success will depend on the integration of agronomy, technology, and policy. By addressing the recurring challenges of logistics, diversification, and market maturity, these systems can transition from pilot projects to robust, scalable components of the European bioeconomy.

### References

- Ajosenpää (2014). Suunnittelulla ja ruo'on hyötykäytöllä tehokkuutta rantojen hoitoon. Elinkeino-, liikenne ja ympäristökeskus- Raportteja 55/2014 [https://www.doria.fi/bitstream/handle/10024/97313/Raportteja\\_55\\_2014.pdf](https://www.doria.fi/bitstream/handle/10024/97313/Raportteja_55_2014.pdf)
- Bayerische Landesanstalt für Landwirtschaft (LfL) (n.d.) MoorWertRechner – Online tool for economic evaluation of paludiculture systems. Available at: [moorwertrechner.de](http://moorwertrechner.de)
- Branchenverband Cannabiswirtschaft e.V. (BvCW) (2025) *Industriehanf (Nutzhanf) in Deutschland: Übersicht in Zahlen. ELEMENTE – Materialien zur*



*Cannabisiwirtschaft, Band 19 (Version 1.5)* (PDF). Berlin: BvCW. Available at: [https://cannabisiwirtschaft.de/wp-content/uploads/2025/02/ELEMENTE-19-Zahlenwerk-Industriehanf\\_v1.5.pdf](https://cannabisiwirtschaft.de/wp-content/uploads/2025/02/ELEMENTE-19-Zahlenwerk-Industriehanf_v1.5.pdf) (Accessed: 18 May 2026).

Christen, M. and Klaiss, M. (2023) *Biohanf: Vielseitiger Hanfanbau – Ernteprodukte und Möglichkeiten*. Merkblatt Nr. 1266. Frick: Forschungsinstitut für biologischen Landbau (FiBL). Available at: <https://www.fibl.org/fileadmin/documents/shop/1266-biohanf.pdf> (Accessed: 18 May 2026).

Confederação dos Agricultores de Portugal & Sindicato dos Empregadores da Agricultura, Silvicultura e Agroalimentar. (2023). Contrato Coletivo de Trabalho para o setor da agricultura, silvicultura e agroalimentar [Collective Labor Agreement for the agriculture, forestry, and agri-food sector]. Diário da República. <https://dre.pt/>

Hanffaser Uckermark eG (2026a) *Ankaufbedingungen für Hanfstroh (gilt 2026) – Strohankauf Landwirtschaft*. Available at: <https://www.hanffaser.de/index.php/strohankauf-landwirtschaft> (Accessed: 4 March 2026).

Hanffaser Uckermark eG (2026b) *Landwirtschaft – Informationen für Vertragspartner (Preise für 2026)*. Available at: <https://www.hanffaser.de/uber-hanf/landwirtschaft> (Accessed: 4 March 2026).

de Jong, S., et al. (2021). Paludiculture as paludifuture on Dutch peatlands: An environmental and economic analysis of Typha cultivation and insulation production. *Science of the Total Environment*, 792, 148161. <https://doi.org/10.1016/j.scitotenv.2021.148161>

Landwirtschaftskammer Nordrhein-Westfalen (2026) *Erfahrungssätze für überbetriebliche Maschinenarbeiten im Rheinland 2026* (PDF). Available at: <https://www.landwirtschaftskammer.de/landwirtschaft/beratung/pdf/erfahrungssatze-rh.pdf> (Accessed: 4 March 2026).

Liu, Y., Zhang, X., Wang, L., & Chen, J. (2023). Economic and environmental assessment of Typha paludiculture for biomass production and carbon sequestration on reclaimed peatlands. *Science of the Total Environment*, 876, 162534. <https://doi.org/10.1016/j.scitotenv.2023.162534>

Moorwertrechner (n.d.) *Economic assessment tool*. Available at: <https://moorwertrechner.de/> (Accessed: 12 May 2026).

Praxis-Agrar / Bundesanstalt für Landwirtschaft und Ernährung (BLE) (2025) *Nutzhanf: Anbau, Ernte und Vermarktungsoptionen* (web article). Available at: <https://www.praxis-agrar.de/pflanze/ackerbau/kulturpflanzenvielfalt-und-fruchtfolge/nutzhanf> (Accessed: 18 May 2026).

Thüringer Landesanstalt für Landwirtschaft (TLL) (2005) *Leitlinie zur effizienten und umweltverträglichen Erzeugung von Faserhanf* (PDF). Jena: TLL. Available at:

<https://www.tll.de/www/daten/publikationen/leitlinien/hanf0805.pdf> (Accessed: 4 March 2026).

Turku University of Applied Sciences (2023). Järviruoko-webinaari [Lake reed webinar]. [https://jarviruoko.turkuamk.fi/uploads/6fddf1dd-webinaari\\_pohja.pdf](https://jarviruoko.turkuamk.fi/uploads/6fddf1dd-webinaari_pohja.pdf)

Van den Akker, J., Fritz, C., & VIP-NL consortium. (2024). Saldoberekening lisdodde (Typha) – economische rekentool voor paludicultuur. VIP-NL Project. Wageningen University & Research. Retrieved from: <https://vip-nl.nl>

Valonia (2016). Ruovikoiden hoito [Reed bed management]. [https://aurajoki.net/wp-content/uploads/2016/05/Ruovikoiden\\_hoito.pdf](https://aurajoki.net/wp-content/uploads/2016/05/Ruovikoiden_hoito.pdf)

Waterschap Amstel, Gooi en Vecht. (2025). Pilot natte teelt bij de boer: Tussenrapportage 2019–2025 (Versie 1.1). Waternet. Retrieved from: <https://vip-nl.nl>

