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D2.1. [REPORT OF CROP MANAGEMENT PRACTICES]

PHYtomanagement as a sustainable feedstock source of lignocellulosic-based high-value BIo-based products for textile applications

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EXECUTIVE SUMMARY

D2.1. presents a comprehensive overview of crop management strategies for selected lignocellulosic species (poplar, birch, willow, miscanthus, and hemp) intended for phytomanagement on marginal lands within the pHYBi project. The deliverable is part of WP2, which focuses on optimising and validating sustainable phytomanagement strategies to produce high-value bio-based products for textile applications. In response to the global challenges of land degradation and the need for sustainable biomass sources, this report compiles the current scientific knowledge and practical experience related to the cultivation of these non-food industrial crops. Each species is analysed in terms of its agronomic requirements, climatic adaptability, water and nutrient needs, pest and disease resistance, harvest timing, and sustainable cultivation practices. Emphasis is placed on their suitability for cultivation on marginal or contaminated soils, with the dual aim of environmental restoration and biomass production. The methodology combines a structured literature review, partner expertise and sustainability indicators to support the selection of crop management practices. The evidence base considers recent peer-reviewed literature, outputs from relevant European projects, and established agronomic knowledge where still applicable. The analysis links each crop to specific marginality constraints, including metal-contaminated soils, hydrocarbon-affected soils, mixed contamination, low-fertility land and salt-affected agricultural soils. Particular attention is given to the role of genotype, clone or cultivar selection, since crop performance under marginal conditions depends not only on species identity but also on the interaction between plant material, soil constraint, climate and management practices. The report concludes by outlining practical implications for the validation and field implementation of these management strategies across the project pilot sites.

1. INTRODUCTION

1.1. DESCRIPTION OF THE DOCUMENT AND PURPOSE

With the rapid increase in the global population there is immense pressure on arable land, and with continuous industrialization of agriculture and other linked industry, the availability of clean and pristine lands that can be used for traditional agriculture is getting limited. However, traditional agricultural practices have had a significant negative impact on the fertile soils due to the excessive or inappropriate use of water, fertilisers and pesticides. As a result of this intensive and unsustainable utilization of available arable land, up to 40% of the world's land is degraded. In fact, between 2015 and 2019, at least 100 million hectares of healthy and productive land were degraded per year (UNCCD, 2024). Such degraded soil systems, resulting from intensive agriculture and other anthropogenic activities, are often referred to as marginal lands, characterised by low fertility, challenging topography, poor soil structure, water scarcity, or contamination, and they present significant hurdles for conventional agriculture (Ahmadzai et al. 2021). Using such land for the cultivation of food crops presents many serious obstacles, which include low yields and economic inefficiency due to environmental degradation. Furthermore, the use of chemical inputs (fertilisers, pesticides) on already fragile marginal soils exacerbates degradation, leading to nutrient runoff, soil erosion, and contamination of water sources (Csikós & Tóth, 2023). In addition, over-irrigation in arid marginal lands can contribute to salinization, leading to loss of biodiversity and increased resource consumption (Demo et al. 2025). Dedicating funds and devotion to cultivating non-productive lands for dietary crops can also lead to detraction of efforts to enhance productivity on genuinely fertile lands, which can ultimately impact regional food security and farmer livelihoods (Giller et al. 2021).

Given the numerous challenges associated with the use of marginal lands, a paradigm shift is needed. Despite being ill-suited for food crops, marginal lands offer a significant potential for alternative, non-food-based industrial applications. Through phytomanagement, with fibre-rich industrial crops, these lands can be used to produce lignocellulosic-based, high-value bio-based products (Mukherjee et al. 2025). The strategic application of fibre- rich plants, not only allows for the sustainable remediation and ecological restoration of marginal lands but also enables the production of value-added bio-based products such as dyes, fibre, wood, timber, and many other materials. Some plants including poplar, birch, willow, hemp, and miscanthus, are all well known for their rapid growth, high biomass yield, and adaptability to various soil conditions, and hence are potential candidates for use in phytomanagement of marginal land (Reinhardt et al. 2022). The biomass produced by these plants is known to have high levels of cellulose, hemicellulose, and lignin, and can be processed into a diverse range of high-value bio-based products (BBPs) (Khan et al. 2025). A particularly impactful application for such BBPs lies within the textile industry, which currently faces significant environmental scrutiny due to its reliance on synthetic fibres and the unsustainable practices of conventional cotton production. Hence, the pHYBi project aims to explore and demonstrate the viability of using phytomanagement strategies on marginal lands to cultivate lignocellulosic crops. The goal is to establish a

sustainable supply chain for high-value bio-based products that can revolutionize the textile industry, offering an environmentally responsible and economically attractive alternative to current practices, while simultaneously revitalizing underutilised land resources.

1.2. WPS AND TASKS RELATED WITH THE DELIVERABLE

This deliverable is linked to WP2 "Sustainable phytomanagement strategies for biomass production on marginal land", and specifically addresses the objectives and expected outcomes of Task 2.1 (Selection of the most suitable species and cultivars for sustainable phytomanagement), which includes assessing the adaptability, resilience, and biomass potential of selected lignocellulosic crops; and Task 2.2 (Development of best-practice cultivation protocols and management strategies), aimed at defining environmentally sound and economically viable practices for each species under consideration. The crop portfolio assessed in D2.1 was not intended as an open-ended screening of all possible phytoremediation crops, but as a structured evaluation of the lignocellulosic, non-food crops already defined in the pHYBi project proposal because of their relevance to marginal land phytomanagement, biomass availability, compatibility with bio-based textile value chains and feasibility for subsequent WP2 validation.

2. METHODOLOGY

The methodology adopted for the development of D2.1 was designed to provide a comprehensive, harmonised, and scientifically robust framework for identifying and analysing crop management practices suitable for sustainable phytomanagement on marginal lands. This section outlines the methodological steps followed, the rationale behind the approach, and the contributions of different partners involved in the work package. The methodological approach was multi-layered and collaborative, combining desk research, expert consultation, and cross-cutting sustainability assessment. It aimed to ensure that the selected lignocellulosic crops (poplar, birch, willow, miscanthus, and hemp) could be appropriately evaluated in terms of their agronomic potential, ecological functions, and compatibility with circular bioeconomy objectives.

2.1. PARTNER COLLABORATION AND COORDINATION

The deliverable was coordinated by PARTICULA and UBU, with active contributions from all project partners involved in crop assessment, field trials, and soil-plant system evaluation. An initial coordination meeting was held at the start of Task 2.1 to align expectations, define responsibilities, and distribute crop assignments. Each partner provided technical input based on their expertise and access to data or experimental sites. In addition, regular bilateral exchanges and progress reviews were conducted during the drafting process. A shared digital workspace facilitated collaborative editing and version control.

2.2. DESK-BASED RESEARCH AND LITERATURE REVIEW

The analysis was based on a structured review of peer-reviewed scientific literature, technical reports, European project outputs, national and international guidance documents, and species-specific databases. The review covered agronomic traits, cultivation requirements, establishment constraints, pest and disease management, biomass productivity, environmental functions and management practices relevant to the cultivation of poplar, birch, willow, miscanthus and hemp on marginal land.

The main sources of information included peer-reviewed journal articles from Scopus, Web of Science and Google Scholar; European project outputs from MAGIC, BIOPLAT-EU, GRACE, Phy2Climate and MIDAS; technical guidance from FAO, EIP-AGRI and national agricultural agencies; and species databases such as EcoCrop, TRY Plant Trait Database and EUFORGEN. The literature search prioritised publications from 2018 onwards, while older publications were retained when they represented established agronomic knowledge, long-term crop management experience or seminal phytoremediation evidence.

Search terms combined crop names with concepts related to marginal land, phytomanagement and crop management, including “poplar genotype phytoremediation”, “willow heavy metal phytoextraction”, “Miscanthus marginal land genotype”, “Miscanthus salinity”, “hemp cultivar marginal land”, “hemp phytoremediation heavy metals”, “industrial crops contaminated land”, “bioenergy crops marginal land”, “soil amendments phytoremediation” and “microbial inoculants phytomanagement”.

The inclusion criteria prioritised studies that: (i) addressed field, semi-field or greenhouse performance under marginal, contaminated or salt-affected soil conditions; (ii) compared genotypes, varieties, clones or cultivars where available; (iii) reported practical management implications such as establishment, fertilisation, irrigation, salinity management, harvesting, coppicing or biomass-use restrictions; and (iv) were relevant to lignocellulosic biomass production and circular bio-based value chains.

The evidence was assessed according to five practical questions: (1) which crops are suitable for each marginality constraint; (2) which genotypes, clones or cultivars show differential performance; (3) which management practices support establishment and biomass production; (4) which phytomanagement function is expected, such as phytoextraction, phytostabilisation, rhizodegradation, erosion control or soil quality improvement; and (5) what limitations or risks should be considered before field validation.

The literature review was complemented with partner expertise and empirical knowledge from previous field trials, greenhouse assays and case-study experience. These inputs helped interpret literature findings under practical conditions and identify management risks, data gaps and operational constraints relevant to the pHYBi case studies.

To avoid treating the selected crops as a simple descriptive list, each species was assessed against a common suitability rationale. The assessment considered: (i) relevance to the pHYBi call objectives and biomass value chain; (ii) evidence of performance on marginal, contaminated or salt-affected land; (iii) availability of suitable genotypes, clones or cultivars; (iv) expected phytomanagement function; (v) management requirements and operational feasibility; and (vi) restrictions linked to biomass safety and final valorisation. This approach allowed the crop portfolio to be prioritised according to project-relevant constraints and implementation needs.

Table 2.1. Evidence base linking crops, marginality constraints and pHYBi relevance

Crop/ Marginality constraint	References/projects	Management implication	Relevance for pHYBi
Poplar/ Metal-contaminated soils; mixed contamination; brownfields	Li et al. (2024); Kovačević et al. (2025); Muraro et al. (2025); Adler et al. (2022); Phy2Climate; MAGIC	Clone/genotype selection is essential because poplar hybrids differ in establishment, biomass, contaminant uptake and stress tolerance. Management should combine adapted clones, good establishment and contaminant partitioning monitoring.	Supports CS#1 and other metal-contaminated sites. Poplar should be treated as a genotype-dependent crop, not as a generic species.
Willow/ Metal-contaminated soils	Kovačević et al. (2025); Urošević et al. (2024); Sandhi et al. (2023); Jiang et al. (2024); MAGIC	Willow is a benchmark for heavy-metal phytoextraction, especially Cd and Zn, but performance is clone-dependent. Management should consider short-rotation coppice and repeated biomass removal.	Willow is retained as a benchmark and alternative woody crop for metal-contaminated land, particularly where phytoextraction through repeated biomass removal is the target function. Its use in specific pHYBi trials depends on project scope, biomass-chain requirements, planting material availability and case-study constraints.
Birch/ Acidic, nutrient-poor or post-industrial soils; mine tailings	Świątek et al. (2024); Jurković et al. (2023); Bierza et al. (2020); Rustowska (2024); MAGIC context for woody crops	Birch is more suitable for stabilisation, pioneer vegetation and ecological restoration than for high phytoextraction. Management should support establishment in poor soils and long-term stabilisation.	Complementary woody species for restoration and stabilisation, but not a primary high-extraction or high-biomass crop without case-specific evidence.
Miscanthus/ Marginal agricultural land; low fertility; hydrocarbon-affected soils; moderate salinity	GRACE; MAGIC; Scordia et al. (2022); Zheng et al. (2022); Pidlisnyuk et al. (2022); Bertola et al. (2024)	Management should distinguish Miscanthus × giganteus from newer hybrids. Genotype choice, establishment support, weed control and biomass-quality monitoring are important, especially under salinity.	M. × giganteus is considered an operational reference genotype for pHYBi because of its availability and field-deployability, while recognising that it does not represent the full Miscanthus genetic pool.
Hemp/ Metal-contaminated soils; low-to-moderate marginality; organic contamination	GRACE; Blandinières and Amaducci (2022); Placido and Lee (2022); Rheay et al. (2021); Scalabrin et al. (2024)	Hemp suitability is cultivar-dependent and limited by salinity, drought, poor structure and biomass-use restrictions after contaminant uptake. Management should include cultivar screening and biomass safety assessment.	Hemp is considered a conditional candidate for selected low-to-moderate stress sites, rather than a broadly suitable option for all marginal land types.

Integration of European project evidence. Evidence from previous and ongoing European projects was considered to support crop selection and management recommendations for marginal, contaminated and underutilised land. GRACE is particularly relevant because it demonstrated the production of miscanthus and hemp on marginal, contaminated and unused land and addressed the importance of identifying suitable hemp varieties and miscanthus germplasm for marginal conditions. MAGIC provides a broader evidence base for industrial crops on marginal lands, including crop databases, agronomic requirements, marginal-land mapping, low-input practices and decision-support approaches. BIOPLAT-EU contributes to the identification and sustainable use of marginal, underutilised and contaminated lands for non-food biomass production. Phy2Climate provides practical evidence for linking phytoremediation pilots with biomass conversion pathways, while MIDAS is relevant for current approaches to industrial crops, climate resilience, biodiversity and low-ILUC biomass production on marginal agricultural land.

These project outputs support a staged approach to crop selection and management based on literature evidence, previous European project results, availability of plant material, suitability for pHYBi case-study constraints, biomass valorisation potential and validation through WP2 tolerance and optimisation experiments.

2.3. STANDARDISED CROP ASSESSMENT AND INTEGRATION OF EXPERTISE

To enable meaningful comparison across species, a structured assessment framework was developed and applied uniformly to each crop. This framework guided the collection and analysis of agronomic parameters including morphology and life form; soil preferences and tolerances; climatic requirements and distribution; water needs and irrigation management; fertilisation and nutrient cycling; pest and disease challenges; harvesting schedules and productivity expectations; and practices associated with sustainable or restorative cultivation. Each of these dimensions was examined in light of its relevance to marginal land conditions, such as low fertility, salinity, contamination, or water stress.

Beyond the desk-based research, the deliverable also drew upon empirical knowledge held by project partners. Field-based observations and lessons learned from ongoing or past experimental trials were integrated into the narrative for each crop. These included case-specific insights on biomass yields, resilience to abiotic stress, pest management practices, and interactions with local soil or microbiota conditions. Examples were contributed from pilot plots or research stations in countries such as Spain, Germany, Poland, and Finland, where these species had been tested under varying environmental and agronomic conditions. These experiences enriched the literature findings by adding context-specific and practice-oriented detail to the crop management strategies. The empirical contributions were not treated as anecdotal or supplementary, but rather as complementary to the scientific evidence base. In cases where literature data were inconsistent or inconclusive, field observations helped identify probable thresholds, management risks, or optimal operational ranges. This dual-source approach enabled the formulation of realistic and regionally adaptable recommendations for each crop.

The assessment framework was therefore not limited to general agronomic descriptors. For each crop, the information was interpreted according to its relevance for pHYBi marginality constraints, namely metal-contaminated soils, hydrocarbon-affected or mixed-contamination soils, saline agricultural soils and low-fertility marginal land. Particular attention was given to whether the available evidence referred to species-level behaviour, genotype- or cultivar-level differences, or operationally available planting material. This distinction is essential because phytomanagement performance depends on the match between crop, genotype or cultivar, soil constraint, climatic context and supporting soil treatments. Accordingly, the crop profiles provide species-level management guidance, while genotype-, clone- or cultivar-level suitability is treated as a key selection criterion for subsequent WP2 tolerance testing, optimisation and case-study validation, particularly for metal-contaminated and salt-affected soils.

2.4. ENVIRONMENTAL CONTEXT, SUSTAINABILITY CONSIDERATIONS AND POLICY ALIGNMENT

To support the replicability and contextual relevance of the proposed strategies, the crop assessments were embedded within an environmental and policy-aware framework. Each species was evaluated in relation to several categories of marginal land, including nutrient-depleted agricultural soils, saline or sodic zones, post-industrial brownfields, sloping or eroded terrains, and wet or flood-prone areas.

These land types were defined based on European land cover datasets, thematic reports from previous Horizon projects, and the working typology adopted within pHYBi. The evaluation of each crop's compatibility with these conditions considered factors such as root system architecture, regenerative potential, stress tolerance, and capacity to provide ecosystem functions such as erosion control or phytoremediation.

The environmental role of these crops was further analysed through their potential to contribute to key ecosystem services. These included the uptake, degradation or immobilisation of contaminants in soil and water; the enhancement of soil organic matter through leaf litter or root biomass; the improvement of soil structure and aeration; the provision of refuge and habitat for beneficial species; and the support of carbon sequestration both above and below ground. Literature and partner knowledge were used to estimate these contributions qualitatively, recognising that their quantification will occur in future deliverables of WP4 and WP5.

In parallel, the crop strategies were assessed for their alignment with European regulatory and strategic frameworks relevant to sustainable biomass production and land restoration. The analysis took into account the criteria defined by the EU Taxonomy Regulation for sustainable economic activities; the eligibility requirements of the CAP and its eco-schemes; the European Green Deal and Farm to Fork targets; and RED II and III directives governing bio-based value chains. The methodology also considered the implications of national and regional bioeconomy strategies, especially with regard to feedstock diversification and land-use efficiency. These policy connections support the potential for long-term implementation, upscaling and funding eligibility of the proposed phytomanagement strategies.

2.5. VALIDATION PROCESS, LIMITATIONS AND FUTURE DEVELOPMENT

To ensure technical coherence, each crop section underwent an internal validation process involving at least one reviewer external to the authoring institution. Reviewers were selected based on complementary expertise and geographic relevance. Their feedback helped correct inconsistencies, refine definitions, suggest additional references, and standardise the level of detail and language across the document. Terminology and measurement units were harmonised across sections to improve readability and analytical consistency. A final quality check was conducted by the WP2 lead team, focusing on scientific accuracy, completeness, and logical flow of arguments.

It is important to recognise the limitations inherent in this methodological approach. First, the data presented are largely derived from literature and expert knowledge, without direct empirical testing within the context of the pHYBi pilot sites. Second, performance metrics such as biomass yield, water use, or nutrient efficiency are highly dependent on local variables such as soil properties, climate conditions, and management intensity, and therefore cannot be generalised beyond a certain range. Third, the long-term ecological and economic impacts of these strategies have not yet been validated and will require multi-seasonal field experimentation. Fourth, the interactions between crop growth and microbiome dynamics remain only partially explored and will be further studied in WP4. Fifth,

risk factors such as invasiveness, pest adaptation, or unintended soil degradation effects are acknowledged but not quantitatively assessed at this stage. Despite these limitations, the methodology provides a scientifically grounded, operationally useful, and policy-relevant foundation for the implementation of phytomanagement strategies in marginal lands. The next steps of the project will involve the testing and refinement of these strategies under real field conditions as foreseen in Task 2.3 and Task 2.5. This will include the installation of demonstration plots; monitoring of crop performance and soil parameters; evaluation of co-benefits in terms of biodiversity and landscape resilience; and further co-creation with local stakeholders to adapt the strategies to regional constraints and opportunities. The methodology presented here will serve as a living framework to guide those processes, while also supporting the integration of pHYBi results into broader European efforts toward sustainable land use and bio-based innovation.

3. CROP MANAGEMENT STRATEGIES BY CROP

3.1. POPLAR

3.1.1. General overview

Populus spp., commonly referred to as poplar, aspen, or cottonwood, is a genus comprising 25-30 species of fast-growing deciduous trees in the Salicaceae family. Native to the temperate and boreal regions of the Northern Hemisphere, poplar species are ecologically and economically significant due to their wide distribution, adaptability, and rapid biomass accumulation. The genus exhibits high genetic diversity and includes species ranging from medium-sized trees to large specimens exceeding 40 m in height and trunk diameters up to 2.5 m. The main features of this species are detailed in **Table 3.1**. Many species are cultivated for forestry, biomass, and industrial uses across Europe, North America, and Asia (Fang et al., 1999; Adler et al., 2022).

Table 3.1. General morphology and characteristics of poplar.

Morphology and growth characteristics	
Family	Salicaceae
Life form	Fast-growing deciduous trees
Main use	Biomass production, pulpwood, land reclamation, and wood-based manufacturing
Used plant part	Primarily stem wood and bark
Growth habit	Upright form (ranging from columnar to spreading crown shape) with extensive root systems and suckering capacity.
Height	15–50 meters
Bark	Smooth and light-coloured with prominent lenticels in young trees; rough and fissured with age in some species
Leaves	Alternately and spirally arranged; variable in shape (triangular, circular, lobed); long petiole
Reproduction	Both sexually (seeds) and asexually (suckering and cuttings)

Poplars are well known for their vigorous root systems, which can extend up to 40 meters from the trunk, and their ability to reproduce clonally via root suckers or fallen branches. These characteristics allow *Populus* to colonize large areas and form extensive clonal stands (Eckenwalder, 1996; Pregitzer, 2008). Due to their rapid growth and ease of propagation, poplars are often selected for short-rotation forestry and land restoration projects, particularly on marginal or disturbed soils (Hall & Heybroek, 1997; Li et al., 2024).

Poplar wood is lightweight, soft, and fine-grained, making it highly versatile in various industries. Its flexibility and close grain make it suitable for a number of applications (Grosser, 2014). It is commonly used for the production of pulpwood for paper manufacturing, as well as inexpensive timber for pallets, plywood, and

packaging materials. Specialized uses include matchsticks, boxes for soft cheeses such as Camembert, and components in the musical instrument and snowboard industries due to its flexibility and uniform texture. The seasoned wood is also favoured for traditional fire-starting tools like bow drills. In addition, the high tannin content in the bark has historically been utilized for tanning leather (Grosser, 2014).

More recently, several studies have demonstrated that the main chemical constituents of poplar sawdust, namely cellulose, hemicellulose, and lignin, can be effectively valorised through integrated biorefinery processes. These approaches yield lignin oil rich in phenolic monomers, fermentable sugars such as glucose and xylose, bioethanol, and cellulose fibres suitable for textile applications like viscose. This shift highlights poplar's growing potential beyond traditional timber, offering a sustainable feedstock for the production of high-value biofuels, chemicals, and bio-based materials through non-GMO, catalytic processing routes (Adler et al, 2022; Fan et al., 2023; Wang et al., 2024; Wu et al., 2024).

Beyond their growing role in biorefinery applications, poplars have long been valued in energy forestry systems, due to their rapid growth, adaptability, and favourable energy return. Their suitability for short-rotation coppice (SRC) cultivation, typically harvested every two to five years, makes them a reliable biomass source for both biochemical and thermochemical conversion routes (Nassi et al., 2010). Reported yields in regions such as the UK and Italy range from 12–16.4 oven-dry tons per hectare per year, demonstrating both high productivity and a positive energy balance. While biochemical processes target fermentable sugars for bioethanol, thermochemical methods such as fast pyrolysis are particularly effective for juvenile coppice wood, offering higher energy recovery (Dou et al., 2017; Kutsokon et al., 2015; Zsuffa et al., 1996).

In addition to their energy applications, species such as *Populus nigra* serve multifunctional roles in agroforestry and land restoration. Commonly planted as windbreaks, they reduce wind erosion and protect adjacent croplands. Their robust root systems improve soil structure and stabilization, supporting key ecosystem services such as erosion control, water retention and the rehabilitation of degraded or marginal land (Zsuffa et al., 1996). These ecological benefits further reinforce the integration of poplar into sustainable land-use strategies alongside their role as a renewable feedstock for the bioeconomy.

Poplars also contribute significantly to riparian zone management and flood mitigation. Species such as *Populus nigra* and *Populus deltoides* tolerate periodic flooding and waterlogged soils, making them well-suited for planting in floodplains and wetland buffer zones (González, 2012; Miao et al., 2017). In restored riverbanks, *P. nigra* rapidly colonizes bare substrate, stabilizing banks by trapping sediments, thus reducing erosion and improving water quality by filtering suspended solids and nutrients (Vanden Broeck et al., 2021). Their roots help aerate saturated soils, enabling aerobic–anaerobic microbial cycling essential for nutrient turnover. Root exudates rich in carbon compounds (e.g., sugars, organic acids, phenolics) support rhizosphere microbial communities, enhancing nutrient cycling and the biodegradation of contaminants (phytostimulation) (Li M et al., 2022).

Poplar SRC systems play an increasingly important ecological role, particularly in intensively managed or homogeneous landscapes. While plantations may not fully replicate the ecological functions of natural forests at broader habitat or landscape scales, they nonetheless contribute significantly to biodiversity and ecosystem function (Brockerhoff et al., 2008). By introducing structural and compositional diversity, poplar plantations enhance habitat availability and provide food resources for a variety of insects, birds, and mammals, especially in monoculture-dominated regions where natural habitats are scarce (Christian et al., 1998; Martín-García et al., 2013; Vanbeveren & Ceulemans, 2019; Oliveira et al., 2024). In agroforestry systems, rows of poplars have been shown to increase landscape heterogeneity and support richer soil microbial communities and denitrification activity compared to crop fields (Beule et al., 2020).

As poplar plantations age, structural features such as snags and nurse logs can further enrich wildlife diversity by offering additional habitat niches (Stitt et al., 2022). Poplars also enhance soil health through rapid biomass production and significant litterfall, which contributes to nutrient cycling and organic matter accumulation. For instance, in Belgian poplar plantations, litterfall accounts for approximately 80% of nitrogen inputs (Meiresonne et al., 2007), while in Mediterranean systems, 60–80% of nutrients are recycled through decomposed litter (González et al., 2020). Moreover, leaf litter releases higher amounts of primary macronutrients into the soil than are taken up by aboveground biomass in marginal conditions, reducing the need for fertilisation and enhancing both the profitability and sustainability of the crop (Pérez et al., 2021). This organic input fosters microbial diversity, improves soil structure, and enhances moisture retention (Liang, 2024). Labile fractions of soil organic matter respond sensitively to poplar-based agroforestry systems, serving as indicators of changes in soil quality (Mao R et al., 2012). These changes, in turn, influence mycorrhizal fungal communities and their role in soil carbon dynamics, as observed in the sustained effects of poplar growth on Eutric Cambisols (Baum et al., 2019).

Additionally, poplar species have emerged as effective candidates for phytoremediation due to their rapid growth, extensive root systems, and high capacity to uptake, degrade, or immobilize environmental pollutants (Chalot, 2024). These trees can accumulate and store trace elements (TEs) within their biomass, particularly in leaf and trunk tissues, while also contributing to the removal of atmospheric pollutants (Doty et al., 2017). Poplars have been successfully employed in the remediation of soils and sludge contaminated with a wide range of harmful substances, including heavy metals, polychlorinated biphenyls (PCBs), trichloroethylene (TCE), and polycyclic aromatic hydrocarbons (PAHs) (Gordon et al., 1998; Justin et al., 2010; Guidi Nissim et al., 2018). Their robust tolerance to contaminated environments, combined with their potential for biomass harvesting, makes them valuable tools in integrated environmental restoration and sustainable land management strategies.

Moreover, poplars are resilient in marginal conditions. Certain species, such as *Populus euphratica*, show important physiological adaptation strategies including thickened cuticles, succulent leaves, and modular leaf traits, and demonstrate remarkable tolerance to drought and salinity, surviving in soils with up to 2%

salinity and reducing water consumption under stress (Fu, Li, & Chen, 2012). Through specialized salt-exclusion mechanisms, such as discharging salty water through portals in its trunks and leaves and seasonal shedding of salt-laden leaves, *P. euphratica* can eliminate up to 99% of NaCl from its xylem sap, showcasing its adaptability to arid environments (Zeng, Yan, & Arndt, 2009; Yao et al., 2024).

3.1.2. Climatic requirements and global distribution

Populus species are widely distributed across the Northern Hemisphere and have been extensively introduced into temperate and humid regions worldwide. Globally, approximately 9.6 million hectares of land are covered by poplar plantations (He et al., 2018). Indigenous poplar stands cover more than 64 million hectares, predominantly in Russia, Canada, and the United States. In Europe, poplar plantations are concentrated in countries such as France, Spain, Hungary, and Italy. Poplars typically thrive in moist sites near water sources and prefer regions with hot summers and cold to mild winters (Mifsud, 2002; Fussi et al., 2010; de Rigo et al., 2016). While 91% of global poplar presence is in natural forests (Sharma et al., 2012), introduced plantations are emerging as a growing component of poplar forestry systems.

3.1.3. Water requirements and soil preferences

The response of different poplar species and clones to soil water availability has not been fully evaluated (Xi et al., 2021). Poplars, including species such as *Populus alba* (white poplar), generally require between 25–38 litres of water per week, depending on tree size, age, and environmental conditions (Imada et al., 2008). Young trees demand more frequent irrigation, while mature specimens tolerate longer intervals between watering. A controlled study by Yang, Liang, and Han (2004) compared the effects of three soil moisture treatments, i.e.: 70%, 55%, and 40% of field capacity, on the growth and water-use efficiency (WUE) of *Populus simonii.* The results indicated that under moderate drought conditions (~55% FC), poplar maintained strong growth and exhibited the highest total WUE, defined as the ratio of biomass to water consumed. Although biomass accumulation was slightly reduced compared to the 70% treatment, the intermediate moisture level provided the most efficient balance between water availability and physiological performance.

Under field conditions, especially during the peak growing season, mature hybrid poplars in SRC systems transpire a substantial portion of total evapotranspiration, typically accounting for around 59% of ET at the stand scale (Bloemen et al., 2017). Despite this, annual water use of poplar SRCs is generally comparable to or lower than that of grassland benchmarks in temperate European regions including Belgium, Italy, and Czechia (Bloemen et al., 2017; Fischer et al., 2013; Zenone et al., 2015). Mean annual crop coefficients of about 0.82 (range 0.65–0.95) reflect these findings and highlight that evapotranspiration during the growing season may exceed grasslands but balances out over the year (Fischer et al., 2018). These overlapping seasonal water use patterns support the sustainable deployment of SRC poplars under moderate irrigation or rain-fed regimes in temperate climates.

However, in more water-limited climates like the Mediterranean, irrigation needs vary widely, depending on soil texture, stand structure, and seasonal dryness

(Oliveira et al., 2020). Field trials using precision subsurface drip irrigation further recommend monitoring soil moisture at a depth of 30–40 cm to guide irrigation practices during the growing season (Paris et al., 2018). This variability means that although poplars are often characterised by high water use, their water footprint remains manageable and highly context-dependent, underscoring the importance of site-specific irrigation and species selection strategies (Shock et al., 2002; Xi *et al.*, 2014). While irrigation generally enhances poplar growth and productivity, it is typically implemented only when it leads to clear economic returns. However, in certain contexts, particularly in arid or drought-prone regions, or during prolonged dry periods caused by extreme climate events, irrigation becomes essential for survival and establishment, even when it is not economically justified, as cultivation would otherwise be unfeasible (Xi et al., 2021).

Optimal growth occurs in loamy, slightly acidic, fertile, well-draining soils under full sun exposure, but soil and water preferences vary significantly by species. Flood-tolerant types such as *P. nigra* and *P. deltoides* thrive in riparian zones and tolerate prolonged waterlogging, contributing to erosion control and nutrient filtration (Godbout et al., 2019; Busont et al., 2023). Conversely, arid-adapted species like *Populus euphratica* survive in saline or drought-prone regions by employing physiological adaptations (Ottow et al., 2005; Fan et al., 2023). Soil texture adaptability ranges from sandy to clayey substrates, and poplars can grow across a wide pH spectrum (4.0–8.0) (Böhlenius et al., 2016a; Böhlenius et al., 2016b; Hjelm & Rytter, 2016; Deraedt & Ceulemans, 1998). Nutrient availability remains a critical factor influencing growth, but the genus plasticity allows it to thrive in both high-quality and marginal soils, supporting uses from biomass production to ecosystem restoration.

Due to the high degree of hybridization in poplar breeding programs, such as those at Phytowelt, there is considerable potential to identify and develop genotypes with enhanced tolerance to both drought and excess moisture. This genetic plasticity makes poplar a promising candidate for afforestation, agroforestry, and biomass production across a wide range of environmental conditions (Monclus et al., 2006; Zsuffa et al., 1996).

3.1.4. Fertilisation

The primary goal of short-rotation poplar plantations is to maximise biomass yield, often on nutrient-poor soils. While nutrient availability, particularly nitrogen and phosphorus, strongly influences growth, long-term studies have indicated that nitrogen fertilisation has no significant effect on the eco-physiological performance of *Populus* and *Salix* species under typical site conditions (Veste et al., 2016). This is largely attributed to the efficient nutrient recycling within these systems; poplar leaf litter and root turnover return substantial quantities of nutrients to the soil, reducing the dependency on external fertiliser inputs (Meiresonne, De Schrijver, & De Vos, 2007). Nonetheless, fertilisation effects can be site-specific. Early-stage poplar plantations, especially those established on severely nutrient-poor soils, benefit significantly from targeted nutrient additions, such as organic mulches, fertigation, or biosolids, to enhance soil fertility, foliar nutrition, and tree growth in

the establishment phase (Fang, Xie, & Liu, 2008; Yan, Dai, & Jia, 2018; Bilodeau-Gauthier et al., 2022; Muraro et al., 2025). Furthermore, phosphorus availability can limit productivity, particularly in intensively managed or nitrogen-fertilised systems, highlighting the importance of balanced fertilisation regimes to sustain optimal growth (Brown & van den Driessche, 2005; Kavka & Polle, 2016; Netzer, Pozzi, Dubbert, & Herschbach, 2019). This nuanced understanding underscores the importance of tailored nutrient management strategies to sustainably maximise biomass yield (Muraro et al., 2025). Recent peer-reviewed research underscores the increasing effectiveness of organic amendments (e.g., biochar, composted substrates, biogas slurry) and biological inoculants (ectomycorrhizal and arbuscular mycorrhizal fungi) in enhancing poplar plantation performance through improved soil health, nutrient availability, stress resilience, and growth (Khosla, Kaur, & Reddy, 2009; Larcheveque, Desrochers, & Larocque, 2011; Yu et al., 2022; Ciadamidaro et al., 2022; Simiele et al., 2022; Muraro et al., 2025). These alternative approaches reflect a shift toward circular, site-tailored nutrient strategies, aligning poplar cultivation with sustainable land management goals. In phytomanagement contexts, these practices should be combined with clone selection, because nutrient acquisition, stress resilience and contaminant partitioning may vary among poplar genotypes.

3.1.5. Pest management

Poplar plantations face a broad spectrum of biotic challenges, including insect herbivores, fungal pathogens, bacteria and viruses, weed competition, and soil-borne pathogens. Effective management requires diversified strategies integrated within an Integrated Pest Management (IPM) framework.

Poplar stands are occasionally affected by herbivorous insects such as the poplar tentmaker moth (E*pinotia tedella*), which causes leaf-rolling and feeding damage primarily on younger trees, though it rarely results in significant economic loss; this aligns with broader lepidopteran damage assessments in poplar, although specific economic impact studies are limited (Royle & Ostry, 1995). Another common defoliator is the poplar leaf beetle (*Chrysomela populi*), identifiable by its red wing cases and metallic-green body. Both adults and larvae feed on leaves, with mating and egg-laying directly on foliage and larvae overwintering in leaf litter. Although *C. populi* is widespread, outbreaks seldom reach damaging levels and often require no intervention (Urban, 2006; La Spina et al., 2010).

Other key insect pests include stem borers such as *Apriona cinerea* and defoliators like *Clostera spp*. and *Lymantria dispar*, which can significantly reduce tree vigour and yield. A. *cinerea* larvae, for example, bore into stems and have caused high mortality rates in young plantations (Singh & Prasad, 1985; Singh, Bhandari, & Verma, 2004). In northwestern India alone, over 65 insect species have been documented attacking Populus deltoides. Control strategies in that region include planting resistant clones, sanitation pruning, biological control agents like *Trichogramma spp*., and targeted insecticides such as carbaryl and cypermethrin (Singh et al., 2004).

Gall inducing aphids and mites induce woody, cauliflower-like galls on poplar buds and shoots. While primarily an aesthetic pest, high mite densities can reduce leaf area, stunt branch growth, and stress trees over multiple seasons. Management commonly includes pruning out galled shoots during dormancy and applying horticultural oils or acaricides at budbreak to suppress emerging mite populations (Floate, 2010, Charles et al, 2014).

Moreover, poplars can also be affected by parasitic nematodes such as *Meloidogyne incognita*, which infect roots, reduce growth, and trigger defensive responses involving changes in gene expression and phenolic compounds (Khan et al., 2017; Baldacci-Cresp et al., 2016).

Among fungal pathogens, rust fungi (*Melampsora spp*.) and septoria cankers (*Sphaerulina* musiva, previously *Septoria musiva*, and S. *populicola*) are among the most destructive in poplar worldwide. These pathogens cause necrotic lesions on foliage and oozing bark cankers that girdle stems, leading to significantly reduced growth and eventual dieback within a few years if unmanaged. They also rapidly adapt in monocultures of susceptible clones, underscoring the importance of resistance breeding, genetic diversity, implementation of regional surveillance programs, and sanitation practices such as pruning infected branches and removing fallen inoculum-laden leaf litter (Cellerino, 1999; Royle & Ostry, 1995; Zhao et al., 2023)

Other important fungal threats include anthracnose caused by *Colletotrichum* spp., which produces leaf lesions and shoot blight; management typically relies on cultural hygiene and occasional fungicide or biological control applications (Zhang et al., 2022). Soil-borne root-rot pathogens such as *Armillaria* spp. and *Phytophthora* spp. compromise poplar root systems and require preventive measures like careful site selection, removal of stumps and infected debris, installation of root barriers, and rotations to non-host species for effective control (Alveshere et al., 2021; Černý et al., 2022)

Venturia populina, responsible for poplar leaf and shoot blight, produces characteristic blackened shoots that bend into "shepherd's crooks," especially common in regions with wet spring conditions. Inoculation experiments and disease surveys confirm that while the pathogen can cause defoliation, its economic impact remains low when resistant clones are planted, infected shoots are pruned, and wet microclimates are avoided through site selection (Newcombe, 2003).

Marssonina leaf spot, caused by *Marssonina brunnea* (including formae speciales), leads to brownish-black lesions on leaves and young shoots, often resulting in premature defoliation and reduced photosynthesis. Genome and pathology studies demonstrate its widespread prevalence and potential to weaken growth. Control measures include planting resistant hybrids and rigorous sanitation, such as removing fallen infected debris (Zhu et al., 2012).

Bark necrosis caused by *Discosporium populeum* manifests as necrotic stem lesions with oozing pycnidia that girdle young stems, especially under environmental stress, hindering sapling development or causing mortality. Recent field observations confirm that the disease is effectively managed through sanitation (removing infected bark), planting stress-tolerant clones, and avoiding high-stress environments such as drought-prone or compacted soils (Kwaśna et al., 2021a).

Bacterial diseases in Populus species, though fewer than fungal pathogens, can significantly impact tree vitality. One of the most characteristic disorders is wetwood, or slime flux, which has been strongly associated with *Lelliottia nimipressuralis* (formerly *Enterobacter nimipressuralis*) (Goychuk et al., 2023). Wetwood develops when anaerobic or facultative anaerobic bacteria ferment the sugars and cellulose of heartwood under low-oxygen conditions, producing volatile fatty acids, organic alcohols, and gases that build internal pressure (Fan et al., 2022). This leads to exudation of foul-smelling liquid from trunk wounds or cracks and causes internal wood discoloration and reduced timber quality. While it seldom kills trees, the damage can be economically significant. No chemical treatments are available; thus, management focuses on avoiding trunk injuries, maintaining tree vigour, and promoting good drainage.

In contrast, vascular wilt and canker diseases in poplar are caused by bacterial pathogens that invade and block the xylem, disrupting water transport. Notable species include *Pseudomonas syringae* pv. populi, *Xanthomonas populi*, and more recently *Pseudomonas aeruginosa*, which has been shown to cause rapid dieback and even tree death within 48 hours in some cases (Kwaśna et al., 2021b; Sharan et al., 2024). Another emerging pathogen is *Lonsdalea populi* (formerly *Lonsdalea quercina* subsp. populi), which causes extensive bark cankers and wilting in hybrid poplars, especially in China and Europe (Li & He, 2019, Zlatković et al., 2020). These pathogens typically enter through wounds and spread systemically, resulting in vascular occlusion, stem necrosis, and wilting. Since no effective chemical control exists, management emphasizes planting resistant clones, practicing sanitation, and preventing mechanical damage that facilitates infection.

Viral diseases remain understudied, poplar mosaic virus (PopMV), classified within the Carlavirus genus, is known to infect various Populus genotypes with differing levels of systemic spread and symptom expression, such as vein yellowing and mosaic patterns. Infection responses vary by genotype, indicating potential for breeding resistant cultivars (Brunt, Stace-Smith, & Leung, 1976; Smith & Campbell, 2004;). Separately, the recent identification of bean common mosaic virus (BCMV) infecting poplar represents an emerging viral threat. Integrated transcriptome and microRNA sequencing analyses have revealed complex host gene expression changes in response to BCMV infection, highlighting new molecular pathways involved in disease development and host defensive mechanisms (Wang et al.,

2023). These findings demonstrate the expanding diversity of viral pathogens affecting poplar and underscore the need for advanced molecular diagnostics and breeding strategies to develop genetic resistance.

Weeds significantly impact poplar health by competing for essential nutrients, impeding establishment, and providing habitat for pests and predators. In controlled pot trials, hybrid poplars grown alongside *Taraxacum officinale* (dandelion) or *Elymus repens* (quackgrass) exhibited dramatic reductions in shoot biomass, from approximately 28 g to less than 1 g over 14 weeks and experienced severely impaired uptake of nitrogen (N), phosphorus (P), and potassium (K) (Kabba, Knight, & Van Rees, 2009). Field studies in Saskatchewan corroborated these findings, showing nitrogen uptake dropped from around 15.8 mmol N/plant without weeds to just 1.7 mmol N/plant in competition (an ~90% reduction). Long-term productivity projections confirmed that weed pressure significantly reduces stemwood yield, especially on poorer soils, and early fertilisation can help partially offset those losses. In Italy's short-rotation poplar systems, weed competition caused yield losses of approximately 26% in the first season and 29% over biennial cycles, with the most detrimental period occurring during the early 30–80 days post-planting (Otto, Loddo, & Zanin, 2010). A 2024 study in Serbia evaluated glyphosate weed-control efficacy across three poplar plantation sites and demonstrated significant improvements in physiological performance (photosynthesis, stomatal conductance, transpiration rate, and water-use efficiency) after weed suppression (Dudić et al., 2024). Efficient weed management during poplar establishment includes intensive vegetation control, particularly plastic or degradable carpet mulching, applied immediately after planting, which significantly increases seedling stem and leaf growth in the first year compared to manual weeding or no treatment (Böhlenius & Övergaard, 2015a; 2015b).

Hemiparasitic plants such as mistletoes (*Viscum album* in Europe and *Phoradendron* spp. in North America) extract water and nutrients from poplars via haustoria, gradually weakening or killing branches. These parasites are commonly managed through pruning of infected branches and strategic host selection, although pruning may not fully eliminate the parasite due to deep haustorial penetration. Some poplar cultivars exhibit resistance mechanisms, including flavonoid accumulation, which help limit mistletoe infestation (Coder, 2008; El Hariri, Sallé, & Andary, 1991; Sallé, Hariri, & Andary, 1994). Similarly, the root-haloparasitic *Lathraea clandestina* can parasitize poplar roots with subterranean, chlorophyll-lacking stems, diminishing host vigour (Atkinson & Atkinson, 2020).

Poplar protection is increasingly focused on biotechnological and ecological precision strategies. Recent advances highlight the use of biocontrol agents such as endophytic fungi and bacteria, which have demonstrated potential in reducing pest populations while minimizing chemical inputs (Busby, Peay & Newcombe, 2015; Naik et al., 2021; Walther et al., 2025). Additionally, entomopathogenic nematodes, represent a promising avenue for future research targeting stem-boring and soil-dwelling pests in poplar (Williams, 2024; Tian et al., 2022). In addition to enhancing tree health by improving nutrient uptake, mycorrhizal fungi, both arbuscular (AMF) and ectomycorrhizal (ECM), have also been documented to strengthen poplar

defences against several pests and pathogens (Pfabel et al., 2012; Dong et al., 2021; Zhang & Tang, 2021; Jiang et al., 2022; Padmanaban et al., 2022).

Molecular diagnostics, including transcriptomic analyses, have identified key defence genes such as lipoxygenase (LOX) involved in jasmonic acid-mediated resistance pathways in poplar (Huang et al., 2022). Genetic approaches such as RNA interference (RNAi) show promise for durable pest resistance in poplar (Jiang et al., 2024; Sharan et al., 2024). Although direct application of marker-assisted selection targeting LOX genes has yet to be demonstrated, candidate defence-related genes, including LOX, WRKY, and MYB, offer valuable targets for breeding or genetic engineering of resistant clones through genome editing tools like CRISPR/Cas (Kovalev et al., 2024). Additionally, microbiome engineering shows emerging potential to enhance pathogen resilience in poplar. In the meantime, microbiome management via soil amendments such as biochar and compost foster beneficial microbial communities, contributing to pest suppression and potentially improving poplar resilience under biotic stress. Biochar has been shown to enhance soil health and microbial dynamics in tree-based cropping systems, offering indirect protection against pathogens (Antonangelo et al., 2025), while in agricultural crops compost amendments can alter root exudation and microbial activity in ways that reduce disease development (Akhter et al., 2015).

3.1.6. Harvest timing and productivity

The timing of harvest and overall productivity are critical factors determining both economic viability and environmental performance. Poplar short-rotation coppice is typically harvested on 2- to 5-year cycles, with 3- to 4-year rotations often representing an optimal balance between biomass yield and resource use efficiency (Fernández et al., 2020; Niemczyk et al., 2016). Studies across temperate Europe report annual dry biomass yields ranging from 1.4 to 14 Mg ha^{-1} yr^{-1} on marginal or degraded lands, heavily dependent on clone selection, site quality, and management practices (Werner et al., 2012; Oliveira et al., 2020; Reinhardt et al., 2022; Landgraf et al., 2020). However, under intensive management (fertile soils, irrigation, expert silviculture), specific clones achieve dramatically higher productivity. For example: 17.9 Mg ha^{-1} yr^{-1} for 'Monviso' in northern Italy during the first rotation (Paris et al., 2011), 23.5–24.0 Mg ha^{-1} yr^{-1} for elite genotypes (including 'Monviso') in Italian trials during the second rotation (Sabatti et al., 2014) and 26.0 Mg ha^{-1} yr^{-1} for 'Hees' in Belgium and 20.8 Mg ha^{-1} yr^{-1} for 'Skado' by the third rotation (Vanbeveren & Ceulemans, 2018). These exceptional yields highlight the critical roles of genetic potential, rotation maturity, and irrigation (González-González et al., 2017; Oliveira et al., 2020).

Yield trajectories vary by rotation: initial increases of 10–46% are common in the second rotation due to root system maturation, followed by stabilization or decline in subsequent cycles (Dillen et al., 2013; Niemczyk et al., 2016; Dănilă et al., 2022). Shorter rotations (2–3 years) maximise annual biomass but intensify soil disturbance and nutrient export. Conversely, longer rotations (5–6 years) reduce greenhouse gas emissions by 15–30% and lower nitrate leaching by up to 50% without significantly compromising total biomass accumulation, highlighting a critical trade-off between annual yield and ecological impact (Schweier et al., 2017; Fernández et al., 2020).

Poplar biomass harvested at earlier stages contains a higher proportion of leaves, bark, and branches alongside wood chips, resulting in a more heterogeneous feedstock. While this variability can influence bioconversion efficiency, integrated biorefinery processes, such as steam-explosion pretreatment, enzymatic hydrolysis, and hybrid thermo-biochemical systems, have successfully utilized early-harvest material to produce fermentable sugars, lignin-derived chemicals, and bioethanol, demonstrating the feasibility of early-harvest biomass valorisation (Dou et al., 2017).

3.1.7. Sustainable cultivation practices

Establishing sustainable poplar plantations begins with the proper handling and planting of cuttings. Poplar cuttings can be planted throughout the spring season once the risk of frost has passed and to minimize physiological stress and ensure optimal regrowth potential. The recommended time for both planting and harvesting operations is between January and March, depending on local climatic conditions. Given their high demand for water and sunlight, it is recommended to establish plantations in open fields with minimal competing vegetation. This reduces resource competition and maximises early growth potential.

Root development can be enhanced by pre-soaking cuttings in water or initiating rooting in soil prior to field transplantation. When planting, approximately two-thirds of the cutting should be buried below ground, with at least one viable bud exposed above the soil surface. The length of the cuttings may vary from 20 cm to 100 cm depending on site conditions. On nutrient-poor or drought-prone soils, longer segments should be buried to increase rooting surface area and minimize desiccation risk in the absence of timely rainfall.

Routine maintenance includes mowing between rows to suppress competing grass species, ensuring that poplar saplings receive adequate sunlight and water. This practice minimizes competition and supports vigorous early growth.

In a recent management practice (February 2025 by Phytowelt), all branches of 5-year-old poplars were pruned, and the main stems were cut back to a height of approximately 1.5 meters. This approach facilitates easier access for harvesting operations and promotes uniform regrowth from coppice shoots, supporting efficient biomass production in subsequent rotation cycles. Such practices are particularly relevant in short-rotation coppice systems aimed at maximising productivity and simplifying harvest logistics.

In terms of long-term sustainability, poplar exhibits a strong regenerative capacity. Trees up to five years old can be coppiced, cut down near the base, stimulating the development of multiple new shoots. Repeated cutting promotes a bushier growth form, resulting in a higher number of stems. Over time, this not only increases biomass yield but also enhances the plant's ability to absorb heavy metals and other pollutants from the environment. Consequently, repeated coppicing in short rotation cycles contributes both to sustainable biomass production and to improved phytoremediation efficiency. However, for contaminated and marginal soils, poplar should be managed as a clone- and genotype-dependent crop, since hybrids may differ substantially in establishment capacity, biomass production, contaminant uptake, translocation patterns and tolerance to site-specific stress conditions.

3.2. BIRCH

3.2.1. General overview

Betula pubescens Ehrh., commonly referred to as downy birch or European white birch, belongs to the Betulaceae family. It is a native species from Northern Europe and Asia, and is adaptable and widespread in temperate and boreal regions (Atkinson 1992; Beck et al., 2016). Birch is a deciduous tree, shedding its leaves seasonally, which influences its management and ecological impact. As a pioneer species, it is notable for its ability to colonize degraded soils, as well as its resistance and tolerance to harsh conditions (Atkinson 1992; Beck et al., 2016). The main characteristics of this species are detailed in **Table 3.2**.

Table 3.2. General morphology and characteristics of birch.

Morphology and growth characteristics	
Family	Betulaceae
Life form	Deciduous tree
Main use	Ecological restoration, pulpwood industry, energy wood production
Used plant part	Above-ground biomass (mainly bark)
Growth habit	Medium-sized tree, moderately fast-growing
Height	Up to 20 meters
Stem	Straight, brown bark (young trees), white smooth bark (mature trees) with horizontal lenticels
Leaves	Ovate, serrated margin, pubescent on the underside, light green
Inflorescence	Male and female catkins; flowers in spring

As pioneer species, birches commonly occur on abandoned lands and are ideal for ecological succession processes, as it improves soil conditions for the establishment of other vegetation. Their pioneering characteristics include rapid growth in youth stages, the ability to grow in unfavourable habitats, the low nutritional demands and seed dispersal by wind. However, they are characterised by low shade tolerance (Jonczak et al., 2020; Savill 2019).

These traits are particularly relevant in marginal and degraded environments, where vegetation establishment is often limited by poor soil conditions. *B. pubescens* exhibits physiological adaptations that allow it to establish and grow under a wide range of habitat conditions, including acidic, wet, nutrient-poor and metal-contaminated soils, although higher biomass production is reported at fertile sites (Farrar, 1995). Its extensive and branched root system contributes to soil stabilisation and improves soil structure. Due to its ability to establish under chemically stressed conditions, birch has been considered suitable for the reclamation of degraded areas (Jonczak et al., 2020).

In this context, *B. pubescens* tolerates heavy metals and has shown potential for the phytoremediation of arsenic- and metal-contaminated soils (Fernández-Fuego et al., 2017a, 2017b; Sánchez et al., 2024). In metal(loid)-polluted soils, birch should be considered primarily as a pioneer woody species for restoration and stabilisation-oriented phytomanagement systems, particularly where the objective is to establish vegetation cover, improve soil structure and functionality, and reduce environmental risk rather than to maximise contaminant transfer to harvestable biomass (Moreira et al., 2021; Sánchez et al., 2024).

Beyond its role in restoration and phytomanagement, birch also has economic and industrial value. Above-ground biomass can be used for energy production, although its combustion quality may vary depending on moisture content and absorbed trace elements. Other uses include forestry, timber production, ornamental planting, pulpwood, firewood, phytoremediation, and production of xylitol and birch sap, highlighting its economic and ecological value (Beck et al., 2016; Savill, 2019).

This biomass potential is relevant in phytomanagement systems where birch may provide a non-food lignocellulosic feedstock for cellulose-, hemicellulose- and lignin-derived products, including potential textile applications. However, biomass produced on polluted soils should be chemically characterised before downstream use because contaminant accumulation may restrict its valorisation pathways (Mukherjee et al., 2025).

Within this framework, *B. pubescens* was selected because it grows well in polluted areas of Asturias, Spain (Fernández et al., 2011), and has also been found in several other metal-polluted sites in the Mediterranean area, where it can accumulate As, Cd, Cu, Pb and Zn (Fernández et al., 2008; Fernández et al., 2011). This background supports the use of plant material originating from polluted environments as a relevant basis for phytomanagement studies, particularly when tolerance, establishment capacity and contaminant allocation are key selection criteria. The birch material considered for the project derives from seeds collected in Asturias from plants growing on heavy metal-contaminated soils. The seeds were germinated under controlled in vitro conditions, and selected individual seedlings were subsequently propagated vegetatively to establish separate clonal lines. The clones were subsequently screened under Cd exposure to assess growth, biomass production, Cd accumulation in leaves and translocation capacity. Clone selection was therefore based not only on metal accumulation, but also on plant performance under stress conditions (Fernández et al., 2008). This previous characterisation provides a relevant basis for using selected *B. pubescens* material in phytomanagement approaches, where tolerance, establishment capacity and contaminant allocation are key criteria.

3.2.2. Climatic conditions and global distribution

Birch trees are adapted to cool-temperate and boreal climates, with average annual temperatures of 2-15°C, tolerating winter lows of -40°C and summer highs of 30°C, highlighting their climate adaptability. Their climate resilience includes high frost tolerance during dormancy, essential for survival in cold climates (Beck et al., 2016; Jonczak et al., 2020; Harr et al., 2021). They exhibit heat sensitivity, stressed by

prolonged periods of high temperatures and drought, helping managing birch trees in warmer climates. While not strongly photoperiod sensitive, growth is stimulated by long day lengths in summer, contributing to biomass production (Atkinson 1992).

B. pubescens is extremely cold-hardy, able to tolerate Nordic winter temperatures, allowing it to thrive in subarctic, boreal, and mountainous regions. It requires abundant sunlight for optimal growth, being a heliophilous species that does not tolerate prolonged shade. Fluctuating day/night temperature (approx. 18/8°C) shows the maximal shoot growth, showing that high day temperature led to a large number of leaves and greater radial growth (Beck et al., 2016; Harr et al., 2021).

It has a wide altitudinal and latitudinal distribution, ranging from lowlands to high mountain areas. Both the northern and elevational distribution limits of *B. pubescens* appear to be determined by exposure to cold and winds in winter, since the species is not particularly wind resistant. Southern distribution limits appear to be determined by Mediterranean summer drought (González de Andrés et al., 2023).

B. pubescens grows next to watercourses on damp slopes. It tolerates waterlogged soils, which enables it to grow in peatlands and swampy areas, forming stands or copses, or in association with other riverside plants. Although prolonged anoxic conditions can limit its development.

B. pubescens is a typical light-demanding pioneer tree that rapidly colonises open ground following a disturbance. Birch also exhibits some resistance to wildfires, which may furthermore favour its establishment. As well as it is considered to be a soil improver giving rise to deacidified soils with increased value for silviculture.

3.2.3. Water requirements and soil preferences

Birch requires a minimum annual rainfall of 500-600 mm, with optimal rainfall at 700-900 mm, essential for determining whether supplemental irrigation is needed. Irrigation is generally not required, except during establishment on dry sites or during prolonged drought, ensuring proper establishment and survival (Jonczak et al., 2020).

Although it tolerates wet soils and even temporary flooding, *B. pubescens* does not exhibit high water-use efficiency. However, its fibrous root system and adaptation to hydromorphic soils enable it to extract water efficiently from shallow and mid-depth soil layers. It tolerates a range of soil moisture conditions, but prefer well-drained soils. They are sensitive to waterlogging and prolonged flooding, highlighting the importance of selecting appropriate sites.

Its water requirement depends on soil type and plant developmental stage. Young plants are more drought-sensitive, while established trees show greater resilience. However, its growth may be limited by summer drought (González de Andrés et al., 2023). Therefore, water availability in the soil, influenced by the proximity of watercourses and land-use management, is crucial for the development of this species. Some recommended actions to address water requirements problems include monitoring irrigation during summer season to ensure moisture in the deeper roots, as well as reducing competition for water by keeping the area near the tree free of grass and other herbaceous plants during the first years of cultivation.

However, in contaminated soils, irrigation should be managed as an establishment-support practice rather than as an intensive productivity input. Water supply should be adjusted to rainfall, soil moisture and plant stress indicators, avoiding excessive irrigation that could enhance percolation, runoff and the leaching of soluble contaminants. This is consistent with phytomanagement approaches aimed at reducing contaminant mobility and off-site transfer, while maintaining sufficient plant growth for soil stabilisation (Moreira et al., 2021).

3.2.4. Fertilisation

Birch has moderate nutrient requirements, preferring soils with adequate nitrogen, phosphorus and potassium range, allowing for targeted fertilisation strategies. They respond well to fertilisation, particularly with nitrogen, which increases growth rates, making it a key element in forestry management (Weih 2003; Huotari et al., 2008).

Organic amendments improve soil fertility and water retention, benefiting plant growth. *B. pubescens* does not require intensive fertilisation, especially in forest soils or low-productivity agricultural lands. It thrives in poor soils due to its ability to form mycorrhizal associations that enhance nutrient uptake. Natural nutrient cycling occurs as leaf litter decomposes, releasing nutrients back into the soil (Weih 2003). However, fertilisation during the first stages of cultivation will be a crucial step to enhance growth and survival of seedlings, overall, in degraded areas, such as the study zone. Even more, it can benefit from organic amendments or inorganic fertilisers for intensive biomass production, as well as, in contaminated soils, amendments such as compost, biochar or industrial by-products (ash, alkaline sludges), improve both nutrient availability and contaminant immobilization (Huotari et al., 2008, Sánchez et al., 2024).

A light fertilisation with a balanced fertiliser (N:P:K) during the first planting year is recommended. Otherwise, additional fertiliser may be applied during spring in the first years of cultivation in the first years of cultivation to enhance the growth of the plants (Weih 2003). In metal(loid)-polluted soils, fertilisation should be conservative and based on soil analytical data. Nutrient inputs and amendments should be selected not only for their effect on plant growth, but also for their influence on contaminant mobility, pH, organic matter, microbial activity and potential contaminant transfer to plant tissues.

3.2.5. Pest management strategies

B. pubescens shows good resistance to pests and diseases, although it can be susceptible to certain fungi (e.g., *Melampsoridium betulinum* and *Piptoporus betulinus*), defoliating insects (e.g., *Agrilus anxius* and *Fenusa pusilla*), and aphids. However, these issues rarely cause significant damage to productivity or survival (Harr et al., 2021). The larvae of the birch leafminer, *F. pusilla*, feed on leaves, causing mainly aesthetic damage. This common pest is typically managed through insecticides or biological control. In contrast, the larvae of the bronze birch borer, *A. anxius*, tunnel into the trunk, leading to dieback and mortality; prevention relies on maintaining overall tree vigour. In addition, the birch bracket fungus, *P. betulinus*, causes brown rot in the heartwood and is controlled through sanitation measures and by avoiding mechanical damage to the trees (Elamo et al., 1999; Green &

MacAskill 2007). Birch rust (*M. betulinum*) produces yellow and red spots on the leaves and is similarly managed by sanitation and minimizing tree injury. Chemical control is rarely necessary, and in natural or restoration settings, ecological management focused on maintaining functional biodiversity is preferred.

Weed competition can be challenging during the early years to reduce competition for resources, so initial management with organic mulching or mechanical weeding (Jonczak et al., 2020; Harr et al., 2021).

The first management priority should therefore be to maintain tree vigour. This includes the use of healthy plant material, appropriate site selection, adequate spacing, reduction of early competition, avoidance of mechanical injuries and maintenance of suitable soil moisture during establishment. Preventing wounds is particularly important because stem and wood pathogens may enter through damaged tissues, while stressed trees can become more vulnerable to borers (EFSA PLH Panel, 2024). Regular monitoring should include visual inspection of leaves, stems and shoots to detect defoliation, leaf spots, rust symptoms, dieback, abnormal leaf colour, stem damage or poor establishment.

Weed and competing vegetation control is particularly important during the first years after planting, when young birch trees are more sensitive to competition for water, light and nutrients (Jonczak et al., 2020; Harr et al., 2021). Mechanical weeding, manual control, organic mulching or selective vegetation management can be used to reduce competition around the trees while maintaining sufficient ground cover to protect the soil. In polluted or degraded soils, pest and disease monitoring should also be interpreted as an indicator of plant stress and establishment success, since contaminant pressure (Alengebawy et al., 2021), poor soil structure or nutrient imbalance may increase susceptibility to biotic damage (Martín-Cardoso et al., 2025).

3.2.6. Harvest timing and productivity

B. pubescens is a fast-growing species commonly used for pulpwood and biomass production. Optimal harvest depends on the intended use, typically occurring during winter dormancy or early spring, once the tree has translocated nutrients to the roots, to minimize sap flow and facilitate handling (Hytönen 2019, 2020).

Harvest methods include manual (chainsaws and axes) for small-scale harvesting and mechanical (feller-bunchers and harvesters) for large-scale operations. In established forest systems, *B. pubescens* can produce between 5 and 12 dry tons of biomass per hectare per year, depending on management, planting density, and environmental conditions. Woody biomass can be used as firewood, chips, or feedstock for pellet production, although moisture content at harvest (ideally <25%) must be considered (Hytönen 2019, 2020; Savill 2019).

Yield is influenced by several factors, including site quality and stand density. Fertile, well-drained soils tend to produce higher yields compared to poor, dry soils. Additionally, thinning the stand can increase the growth rate of individual trees and improve timber quality.

For biomass produced on contaminated soils, harvest timing and productivity should be assessed together with contaminant distribution among plant fractions. Leaves, bark, branches and woody tissues may differ in their contaminant load; therefore, the suitability of birch biomass for further characterisation or valorisation should not be assumed before analytical confirmation.

3.2.7. Sustainable cultivation practices

Sustainable cultivation practices for birch should integrate low-input forestry principles with the specific precautions required for phytomanagement of marginal or polluted soils. Under general restoration or forestry conditions, management should focus on maintaining soil cover, avoiding soil compaction, reducing unnecessary mechanical disturbance, favouring natural nutrient cycling and controlling early competition from grasses, shrubs or invasive vegetation (Beck et al., 2016; Jonczak et al., 2020). Since birch is a light-demanding species, young trees should be established in open areas with limited canopy competition, and vegetation control during the first years should preferably rely on mechanical or manual methods rather than intensive chemical inputs (Jonczak et al., 2020).

When birch is cultivated on metal(loid)-polluted soils, these practices should be adapted to a stabilisation-oriented phytomanagement approach. Soil preparation should be limited and localised around planting points to improve rooting conditions while avoiding erosion, dust generation, runoff or redistribution of polluted material. Existing vegetation cover should not be removed indiscriminately when it contributes to surface stabilisation, although direct competition around young trees should be reduced during establishment. This approach is consistent with phytomanagement strategies aimed at establishing vegetation cover, improving soil functionality and reducing contaminant mobility and off-site transfer (Moreira et al., 2021).

The establishment phase is especially important when clonal birch material is used. Selected clones propagated in vitro should undergo gradual acclimatisation before transfer to contaminated soils, allowing the development of a functional root system and adaptation to ex vitro conditions. Acclimatisation under high-humidity conditions, followed by progressive transfer to uncontaminated soil and then to greenhouse or outdoor conditions, can improve establishment before exposure to polluted substrates. Field planting should preferably be carried out during the dormant period, when plants are outside the active growing season and transplant stress is reduced. Under Atlantic conditions in northern Spain, local recommendations indicate planting from autumn to early spring, during the dormant period (Rodríguez et al., 2009). This step is particularly relevant in phytomanagement trials, where early plant mortality may compromise vegetation cover, contaminant stabilisation and biomass assessment.

Water, nutrient and amendment management should be conservative and based on site-specific conditions. Irrigation, when needed, should support establishment during dry periods rather than maximise productivity, avoiding excessive water inputs that may favour leaching, runoff or contaminant mobilisation (Moreira et al., 2021). Fertilisation and amendments should be selected not only for their effect on

plant growth, but also for their influence on pH, organic matter, microbial activity and contaminant mobility, since soil pH strongly controls the mobility and availability of many potentially toxic elements in contaminated soils (Kicińska et al., 2022).

Microbial inoculants, mycorrhizae or plant-growth-promoting bacteria may support birch establishment in degraded soils by improving nutrient acquisition, stress tolerance and rhizosphere functioning (Mesa et al., 2017). However, their effectiveness under contaminated field conditions should be validated through appropriate controls and assessed together with plant survival, growth, stress indicators, soil biological response, contaminant mobility and contaminant allocation in plant tissues (Moreira et al., 2021).

Pest and disease management should rely on preventive and low-impact strategies. Regular inspections should be used to detect defoliation, fungal symptoms, dieback, abnormal leaf colour, stem damage or poor establishment. In polluted or degraded soils, these observations are relevant not only for crop protection, but also as indicators of plant stress and site suitability, since heavy metal stress, poor soil structure or nutrient imbalance may affect plant vigour and susceptibility to biotic damage (Alengebawy et al., 2021; Martín-Cardoso et al., 2025). Preventive measures should include healthy plant material, avoidance of mechanical injuries, adequate spacing, control of excessive competition and maintenance of plant vigour. Chemical control should be avoided unless strictly necessary and justified.

When birch is cultivated on contaminated soils, harvesting and biomass management should consider not only productivity, wood quality and operational feasibility, but also contaminant allocation within plant tissues. Since leaves, bark, branches and woody tissues may differ in contaminant concentrations, the suitability of birch biomass for downstream use should be confirmed analytically before valorisation, further characterisation or disposal decisions are made.

Overall, sustainable birch cultivation on contaminated marginal soils should aim to establish a healthy woody cover, improve soil functionality, reduce erosion and contaminant dispersion, and generate biomass whose quality and contaminant load can be assessed under controlled criteria. Management decisions should be guided by measurable indicators such as survival, growth, plant health, soil properties, contaminant mobility, contaminant concentration in plant tissues and biomass suitability for downstream uses.

3.3. WILLOW

3.3.1. General overview

Salix atrocinerea Brot., commonly referred to as grey willow or large grey willow, is a deciduous shrub or small tree native to Western and Central Europe, particularly prevalent in the Iberian Peninsula. It belongs to the Salicaceae family and is one of the dominant willow species in Atlantic climates, but willows thrive in diverse environments across the Northern Hemisphere. It typically grows as a multistem small tree reaching 8–10 m in height and the species shows high variability (**Table 3.3**), including natural hybrids with other willows (Bergkvist & Ledin 1998; Durán-

Gómez 2019). Known for its rapid growth, tolerance to waterlogging, and capacity to colonize disturbed and marginal lands, *S. atrocinerea* primary uses includes bioenergy (biomass production), bioengineering (erosion control), phytoremediation, and as raw material for basketry, paper, and biocomposites, reflecting their versatility and ecological importance (Kuzovkina 2008; Kovačević et al., 2025).

Table 3.3. General morphology and characteristics of willow.

Morphology and growth characteristics	
Family	Salicaceae
Life form	Deciduous shrub or small tree
Main use	Ecological restoration, biomass production, soil stabilization
Used plant part	Above-ground biomass
Growth habit	Multi-stemmed or single-stemmed with dense canopy
Height	Up to 10-12 meters
Bark	Greyish, fissured with age
Leaves	Oblong to lanceolate, grey-green, finely toothed, densely hairy on the underside
Inflorescence	Dioecious catkins appearing before or with leaves in early spring

As pioneer species, willows commonly occur on abandoned lands and it is ideal for ecological succession processes, as it improves soil conditions for the establishment of other vegetation. Their pioneering characteristics include rapid growth in youth stages, the ability to grow in unfavourable habitats, the low nutritional demands and seed dispersal by wind. In addition, as a fast-growing species with high biomass accumulation potential and coppicing capacity, *S. atrocinerea* can play an important role in revegetation of degraded lands and short-rotation woody systems.

S. atrocinerea has shown tolerance to heavy metals and potential for the phytoremediation and phytomanagement of arsenic- and metal-contaminated soils (Álvarez et al., 2003; Freitas et al., 2014; Navazas et al., 2019, 2022). Previous studies have reported that *S. atrocinerea* can accumulate Zn, Mn and As primarily in roots, which may contribute to reducing their mobility in the environment (Álvarez et al., 2003; Navazas et al., 2019). Therefore, in metal(loid)-polluted soils, willow represents a relevant woody candidate because of its fast growth, coppicing capacity, tolerance to wet marginal environments and potential for contaminant uptake or stabilisation. However, its use should be accompanied by strict monitoring of contaminant allocation in plant tissues since high biomass production can also imply higher contaminant transfer to harvestable fractions.

Willow biomass is of particular interest as a renewable lignocellulosic feedstock because short-rotation willow systems can provide continuous woody biomass production on marginal or degraded land (Labrecque et al., 2023). This biomass can be processed into cellulose-, hemicellulose- and lignin-derived fractions, which are

widely recognised as key building blocks for bio-based materials and chemicals (Baker et al., 2022). Therefore, willow can be considered a promising candidate for linking phytomanagement with biomass valorisation, particularly in areas where conventional food or feed production is not suitable.

The willow plant material considered for phytomanagement applications consists of a selected S. atrocinerea clonal line vegetatively propagated from an individual seedling obtained from seeds collected from a tree naturally growing at the Nitrastur site, a multi-trace-element polluted area in Asturias, Spain. This clone was selected because of its high tolerance to As and its capacity to take up this metalloid, and it has been previously characterised under controlled exposure conditions in terms of As uptake, speciation and detoxification responses (Navazas et al., 2019). Its origin from the Nitrastur site, together with its documented tolerance to As and capacity for contaminant uptake, makes it particularly relevant for evaluating willow-based phytomanagement approaches where phytoextraction potential, plant establishment, biomass production and contaminant allocation must be considered together.

3.3.2. Climatic conditions and global distribution

Willows thrive in temperate climates with average annual temperatures of 5-25°C, tolerating winter lows of -30°C and summer highs of 35°C, which is indicative of their broad adaptability. Their climatic resilience includes frost tolerance, surviving prolonged freezing due to dormancy mechanisms, which is crucial for survival in colder climates. Willows are drought-sensitive and require consistent soil moisture, indicating the need for adequate water, particularly during dry periods (Rosenqvist et al., 2000; Kuzovkina & Quigley 2005; Raposo et al., 2020).

S. atrocinerea is well adapted to temperate and Atlantic climates with mild winters and high annual precipitation. It thrives in areas receiving more than 700 mm of annual rainfall and tolerates a wide range of temperatures, although it performs best in cool, moist environments (Dickmann 2006; Linderson et al., 2007). Willow shows a degree of climatic resilience, particularly through its frost tolerance, as it can survive prolonged periods of freezing thanks to effective dormancy mechanisms. However, it has limited drought tolerance and requires consistent soil moisture to maintain healthy growth.

It can withstand seasonal flooding and temporary waterlogging, making it ideal for wetlands, riparian zones, and restored peatlands. Its growth slows under prolonged drought or in compacted, poorly aerated soils. The species leafs out early in spring and maintains photosynthetic activity until late autumn, contributing to high annual productivity (Mola-Yudego & Aronsson 2008).

With a growing season of 120–180 days and growth ceasing at temperatures below 5°C, the growing season influences biomass accumulation and harvest cycles. As long-day plants, their growth peaks in summer under 14+ hours of daylight, explaining why willow growth is most vigorous during summer months.

3.3.3. Water requirements

As a hydrophilic species, *S. atrocinerea* requires consistent soil moisture and is typically found along rivers, wetlands, and moist forest margins. Willow requires a minimum annual rainfall of 500-700 mm, with optimal rainfall at 800-1000 mm, which is essential for understanding their water needs and whether irrigation is necessary (Linderson et al., 2007; Isebrands & Richardson 2014; Bonosi et al., 2010).

It is highly tolerant of flooding and waterlogged conditions due to its ability to form adventitious roots and aerenchymatous tissues under hypoxic stress, allowing them to thrive in wet environments (Linderson et al., 2007).

Irrigation is particularly important during establishment (first 1-2 years) and in regions with less than 500 mm of rainfall to ensure successful growth. While it can survive in periodically dry conditions, optimal growth is achieved in soils with high water availability. During droughts, it responds with leaf wilting and reduced biomass production. Its deep and fibrous root system enables it to efficiently utilize both surface and subsoil moisture. Deep-rooted varieties can access groundwater, reducing irrigation needs and enhancing drought tolerance. They exhibit high water-use efficiency, producing 8–10 g of biomass per kg of water, outperforming many C3 crops, making them a sustainable choice (Linderson et al., 2007). In contaminated sites, the high water demand of willow must be considered together with contaminant transport risk, since water availability is a key factor controlling willow establishment and biomass production (Linderson et al., 2007). Irrigation or planting in moist areas should therefore be managed carefully to support establishment while avoiding enhanced leaching, runoff or mobilisation of soluble pollutants, in line with phytostabilisation approaches aimed at reducing contaminant dispersion and off-site transfer (Moreira et al., 2021).

3.3.4. Fertilisation

Willows have moderate nitrogen demand (60-100 kg/ha/yr) and low phosphorus and potassium needs, guiding fertilisation practices to optimise growth without excessive fertiliser use (Isebrands & Richardson 2014). *S. atrocinerea* is a low-input species but responds positively to soil fertility, especially nitrogen availability.

Organic fertilisation can be particularly suitable for willow systems because willows can efficiently use nutrient-rich organic residues, while leaf litter decomposition and root turnover contribute to internal nutrient cycling and reduce dependence on mineral fertilisers (Rosenqvist et al., 2000). In addition, rhizodeposition and associations with rhizospheric microorganisms can stimulate microbial activity and improve nutrient availability in the root zone (Baum et al., 2015; Navazas et al., 2022). These processes are relevant in marginal soils, where maintaining soil biological activity and nutrient cycling can support long-term stand productivity.

In contaminated soils, fertilisation should be adapted to the intended phytomanagement function of willow. If the objective is mainly biomass production, moderate nutrient inputs may support establishment and coppice regrowth, as fertilisation has been reported to increase willow production, particularly on less fertile or marginal sites (Castaño-Díaz et al., 2018). However, if willow is used for stabilisation-oriented phytomanagement, fertilisation and organic amendments should be managed carefully to avoid increasing metal(loid) solubility, leaching or

undesirable transfer to harvestable stems and branches. This precaution is particularly relevant because amendments or mobilising agents can modify metal availability and uptake in willow, sometimes increasing plant stress or affecting growth (Meers et al., 2007), whereas phytostabilisation-oriented strategies should prioritise the reduction of contaminant mobility and off-site transfer (Moreira et al., 2021). This is particularly important because willow can produce large amounts of above-ground biomass and may accumulate contaminants depending on soil properties, amendment type and plant tissue.

3.3.5. Pest management strategies

S. atrocinerea has good resistance to pests and diseases, though it can be affected by several pests, especially under intensive cultivation. Common pests include the blue willow beetle (*Phratora vulgatissima*) which defoliates young shoots, the willow leaf beetle (*Plagiodera versicolora*) whose larvae skeletonize leaves, and rust fungi (Melampsora spp.), causing leaf spots and necrosis (Björkman et al., 2000; Samils et al., 2001; Pei et al., 2005). The management of beetles is primarily achieved through the use of insecticides or biological control, while fungal pathogen is controlled through sanitation practices and the prevention of tree damage.

Management should be based on regular monitoring during the growing season, particularly after coppicing and during early shoot development, when defoliation can affect biomass production (Björkman et al., 2000). Preventive strategies should include healthy planting material, appropriate stand design, maintenance of plant vigour and, where possible, the use of tolerant or genetically diverse willow material to reduce pest and disease risk (Tubby & Armstrong, 2002).

Weed competition is especially important during establishment before canopy closure. Mechanical weeding, manual control, mulching or selective vegetation management can be used during the first years to reduce competition for light, water and nutrients (Tubby & Armstrong, 2002).

3.3.6. Harvest timing and productivity

In short-rotation coppice systems, *S. atrocinerea* is typically harvested every 2–4 years, depending on site conditions and desired biomass quality (Tubby and Armstrong, 2002; Isebrands and Richardson, 2014; Vanbeveren et al., 2015). The ideal time for harvesting is during the winter dormancy or early spring when moisture content in stems is reduced and nutrient translocation to roots has occurred, ensuring high yield.

Harvest methods include manual (chainsaws and axes) for small-scale harvesting and mechanical (feller-bunchers and harvesters) for large-scale operations. Post-harvest, chips are dried to <20% moisture for combustion or pelletizing, maintaining quality and usability of willow biomass (Vanbeveren et al., 2015).

Annual dry biomass yields range from 8 to 15 t/ha/year, with higher values under favourable conditions and fertilised regimes. The species responds well to

coppicing, with vigorous regrowth and increasing productivity after the first rotation (Vanbeveren et al., 2015).

When short-rotation willow systems are established on contaminated soils, coppicing frequency and harvest timing should be defined not only according to biomass yield and operational feasibility, but also according to contaminant accumulation in harvestable tissues. Since stems, bark, branches and leaves may differ in their contaminant concentrations, biomass quality should be assessed before any downstream use is proposed. Therefore, willow biomass produced under phytomanagement conditions should be chemically characterised to determine whether specific fractions are suitable for further processing, require restricted use, or should be managed as potentially contaminated material.

3.3.7. Sustainable cultivation practices for the crop

Sustainable cultivation practices for willow should integrate short-rotation woody crop management with the specific precautions required for phytomanagement of marginal or polluted soils. Under general conditions, willow contributes to sustainable land management through rapid biomass production, coppicing capacity, soil stabilisation, erosion control, nutrient cycling and habitat provision. Soil conservation can be supported by intercropping or ground-cover management, including legumes such as clover, provided that competition with young willow plants is controlled during establishment (Aronsson & Perttu, 2001; Volk et al., 2004; Tubby & Armstrong, 2002). In addition, the dense willow root system can stabilise riverbanks, reduce sediment movement and help protect water quality (Dimitriou & Aronsson, 2007). Willow systems may also contribute to carbon storage, with values of around 25-30 t C ha^{-1} over a 20-year cycle reported for some systems, while supporting biodiversity and providing habitat for different species (Kuzovkina, 2008; Mola-Yudego & Aronsson, 2008; Rytter, 2012). These characteristics, together with its low input requirements and adaptability to marginal sites, make willow a relevant species for sustainable land restoration (Rowe et al., 2009; Rytter, 2012).

In conventional short-rotation coppice systems, sustainable management should prioritise healthy planting material, appropriate spacing, early weed control, sufficient soil moisture during establishment, moderate nutrient inputs and harvesting during dormancy to promote regrowth while limiting unnecessary inputs (Tubby & Armstrong, 2002; Isebrands & Richardson, 2014). When clonal willow material is used, establishment should include a gradual acclimatisation phase before transfer to contaminated soils. *In vitro*-propagated plants should develop a functional root system, adapt progressively to *ex vitro* conditions and establish in uncontaminated soil before exposure to polluted substrates. This step is particularly relevant in phytomanagement trials, where early plant mortality may compromise vegetation cover, contaminant stabilisation and biomass assessment.

When willow is cultivated on contaminated or degraded soils, management should be adapted to a risk-aware phytomanagement approach. Willow has been widely reported as a suitable genus for vegetation filters, wastewater treatment, soil remediation and phytomanagement of metal-polluted sites, although performance

depends strongly on species or clone, soil properties, contaminant type and management conditions (Aronsson & Perttu, 2001; Meers et al., 2007; Jensen et al., 2009; Matanzas et al., 2021). Site selection is particularly important because willow performs best in moist soils, but high-water availability may also favour contaminant transport if drainage, runoff or groundwater connection are not properly considered (Linderson et al., 2007; Moreira et al., 2021). Soil preparation and weed control should therefore minimise disturbance, erosion, dust generation and redistribution of polluted material, while preserving stabilising vegetation cover where possible. This is consistent with phytomanagement strategies aimed at reducing contaminant mobility, exposure and off-site transfer (Moreira et al., 2021).

Water, nutrient and amendment management should be aligned with the intended phytomanagement function. If the objective is biomass production on marginal but non-contaminated land, moderate fertilisation may support establishment and coppice regrowth, particularly on low-fertility sites (Castaño-Díaz et al., 2018). In metal(loid)-polluted soils, however, irrigation, fertilisation and organic amendments should be managed carefully to avoid increasing contaminant solubility, leaching or undesirable transfer to harvestable biomass. Microbial inoculants or rhizosphere-based strategies may support willow establishment and nutrient cycling, but their performance under contaminated field conditions should be validated through appropriate controls (Navazas et al., 2022).

Harvesting and biomass management are critical when willow is grown on contaminated soils. Coppicing frequency and harvest timing should not be defined only according to yield, but also according to contaminant allocation in stems, bark, branches and leaves. Willow species can accumulate metals differently among plant organs, and this distribution can determine whether biomass fractions are suitable for further processing or should be managed as potentially contaminated material (Meers et al., 2007; Navazas et al., 2019). Before any downstream use is proposed, willow biomass should therefore be chemically characterised to determine whether specific fractions are suitable for further processing or require restricted use (Mukherjee et al., 2025).

Overall, sustainable willow cultivation on contaminated marginal soils should aim to combine biomass production, soil stabilisation, environmental risk reduction and biomass safety assessment. Management decisions should be guided by measurable indicators such as establishment success, coppice regrowth, biomass yield, soil moisture, plant health, contaminant mobility, contaminant concentrations in plant tissues and suitability of the harvested biomass for downstream uses.

3.4. MISCANTHUS

3.4.1. General overview

Miscanthus x giganteus (MG), commonly referred to as giant Miscanthus, is a high-yielding perennial grass belonging to the Poaceae family. Originating from Eastern Asia, specifically China, Japan, Korea, and Taiwan, MG is a sterile hybrid derived from a cross between *Miscanthus sinensis* and *Miscanthus sacchariflorus* (Zhengyi et al., 1994). Due to its superior biomass productivity and efficiency, MG has gained

considerable attention in the European Union, USA, and globally as a prominent biomass and energy crop (Lewandowski et al., 2000; Scordia et al., 2022). For marginal and salt-affected soils, this suitability should be interpreted at genotype level. Miscanthus × giganteus is used here as an operational reference genotype because of its availability and field-deployability, but other Miscanthus hybrids may show different responses under salinity, low fertility or contamination stress. The main features of MG are detailed in **Table 3.4**.

Table 3.4. General morphology and characteristics of miscanthus.

Morphology and growth characteristics	
Family	Poaceae
Life form	Graminoid (grass)
Main use	Biomass energy, industrial raw material
Used plant part	Above-ground biomass
Growth habit	Perennial, tufted or rhizomatous growth
Height	Up to 4 meters
Stem	Slender to robust, erect, solid culms
Leaves	Large, linear, flat with distinct white mid-rib
Inflorescence	Large panicle of racemes; sterile hybrid (no viable seeds)

MG's crop productivity depends on solar radiation, interception efficiency, and converting sunlight energy into plant biomass. Under field conditions, MG achieves peak CO2 assimilation levels of 40 µmol $m^{-2}s^{-1}$. Interception efficiency (εi) depends on canopy architecture, leaf-area index, and growing season duration. MG has achieved εi values of 0.80 in the midwestern US, small plot trials achieved an εi of 0.72, while European tests showed εi values ranging from 0.32 to 0.83 over the growing season. For MG plantations intended for heat production, the surface power production density is 0.6 W m^{-2} per 10 tons of yield per hectare, translating to 1.8 W m^{-2} for a 30-tonne yield per hectare.

MG mature yields range from 20 to 35 bone-dry tons per hectare per year, three times more biomass per hectare than pine plantations, making it a high-yielding crop compared to other biomass crops. Consistent biomass composition with low moisture (<15%), low ash, and minimal mineral content at harvest, facilitating high-quality fuel and bioenergy production.

A defining advantage of MG is its minimal input requirements: low fertilisation and pesticide usage reduce production costs and lower environmental impacts; and the robust resistance to pests and diseases prevalent outside its native Asian habitat (Pude & Bliesener, 2011). MG provides notable environmental and agronomic advantages like: carbon sequestration, since demonstrates high carbon capture rates, removing up to 50% more atmospheric carbon and sequestering up to 80% more carbon in soil compared to pine plantations per hectare annually; soil health improvement due to its extensive, deep root system enhances soil structure, reduces

erosion, and increases water retention and organic matter content; is tolerant to various adverse conditions, including drought, salinity, and heavy metals, enabling successful cultivation in marginal and abandoned lands unsuitable for food production; and offers habitats for wildlife, pollinators, and beneficial insects, thus promoting biodiversity within agricultural ecosystems (Bonin et al., 2014). Moreover, this crop can have significant economic benefits like the diversification of agricultural income streams, especially beneficial where traditional farming faces climatic or economic challenges; and creates local job opportunities in rural areas through its cultivation, harvesting, and processing cycles (Pyter et al., 2009). Is highly versatile, and can be used as feedstock for bioenergy, it is particularly valuable for combustion or biofuel conversion due to its high calorific value and low ash content. Besides, its fibres have widespread applications, including pulp and paper production, building materials, insulation, packaging materials, lightweight concrete, medium-density fibreboard, nano-enabled bio-based materials, biodegradable polymers, and animal bedding (with high absorbency and comfort) (Pude et al., 2005).

In summary, MG is recognized globally for its high productivity, efficient resource use, low-input requirements, environmental benefits, and versatile industrial applications (Scordia et al., 2022; Bertola et al., 2024). These attributes make MG a promising sustainable solution for biomass and bioeconomy initiatives worldwide.

3.4.2. Climatic conditions and global distribution

MG is a highly adaptable plant capable of growing in a wide range of climates, from temperate regions to colder zones. Unlike other C4 crops, it maintains high photosynthetic activity even at relatively low temperatures, allowing it to thrive in climates where other biomass crops might struggle (Long 1983). MG can develop photosynthetically active leaves at temperatures as low as 8°C, although its growth ceases if temperatures drop below 6°C (Lewandowski et al., 2000; Beale et al., 1999). This resilience enables it to establish itself in regions of Northern Europe, Scandinavia, and Russia, as well as in temperate areas of North America. During summer, MG benefits from its high interception efficiency (εi), which varies between 0.32 and 0.83 depending on the season and location, allowing it to absorb and convert large amounts of solar radiation into biomass. In midwestern U.S. field trials, MG reached an εi value of 0.80, demonstrating its potential for efficient energy conversion (Beale & Long 1997; Lewandowski et al., 2016).

As the seasons progress, MG follows a well-defined growth cycle. In autumn, the plant transfers nutrients from the leaves to the rhizomes, ensuring nutrient conservation and promoting underground storage. At this stage, leaves naturally fall, creating a protective layer of organic matter on the soil, improving its structure and enhancing moisture retention. This natural cycle makes MG particularly effective in nutrient-poor or degraded soils, as it helps build organic matter over time (Caslin et al., 2010; Bertola et al., 2024). Although late spring frosts can affect its initial establishment, commercial MG clones have survived winter temperatures as low as -14°C (Lewandowski et al., 2016). This level of cold resistance gives MG a considerable advantage over other biomass crops, such as maize, which typically require higher temperatures for growth (Lewandowski et al., 1997). In some cases, MG has been successfully cultivated even in high-latitude regions like Sweden and

Finland, where its ability to regrow after winter dormancy has been well-documented (Beale et al., 1997).

MG is cultivated in diverse climatic zones worldwide, although genotype choice can influence performance under marginality constraints such as salinity or low fertility (Zheng et al., 2022):

- Mediterranean climates (Spain, Italy, Greece): MG grows well under these conditions as long as it receives sufficient precipitation or supplemental irrigation. However, dry conditions can limit biomass production if water availability falls below 600 mm of annual rainfall (Beale et al., 1999).
- Central and Northern Europe, United States, and Canada: The longer growing season in these temperate zones allows for high biomass yields, particularly when combined with adequate soil fertility and water availability.
- High-latitude regions (Sweden, Finland): Although growth is slower in colder climates, MG has demonstrated a strong capacity for regrowth and biomass accumulation, making it a viable bioenergy crop even in marginal lands (Plazek et al., 2014).

3.4.3. Water requirements and soil preferences

MG is a crop recognized for its exceptional water-use efficiency, allowing it to thrive in various moisture conditions and soil types. One of its key advantages is its deep and extensive root system, which can reach depths of over 2.5 to 3 meters. This root structure enables the plant to access water from deeper soil layers, reducing its reliance on surface precipitation and making it highly drought-tolerant (Beale et al., 1999).

For optimal growth, MG requires a minimum annual rainfall of 600 mm, though it achieves its highest productivity at around 800 mm per year (Beale et al., 1997). In cases where rainfall falls below this threshold, supplemental irrigation may be necessary, particularly during the establishment phase to ensure proper rhizome development and early stand establishment (Caslin et al., 2010). Once established, however, MG demonstrates remarkable resilience to drought conditions by storing energy and nutrients in its rhizomes, enabling regrowth even after prolonged dry periods (Plazek et al., 2014). MG has a high water-use efficiency compared to other bioenergy crops. Under rain-fed conditions, it produces 9.5 grams of biomass per kilogram of water transpired, which is significantly higher than many other C4 grasses. The minimum water requirement per ton of biomass produced is 11 mm of precipitation per hectare, making it a more water-efficient alternative to maize and other energy crops (Lewandowski et al., 2000).

Additionally, MG can be successfully grown in rewetted peatlands, as demonstrated in Tuscany, Italy, where it was cultivated on restored wetland soils with minimal productivity loss (Ciccolini et al., 2013). Although some studies suggest that excessive moisture might hinder growth, research shows that MG can tolerate temporary flooding without significant biomass reduction (Giannini et al., 2014). However, long-term waterlogging should be avoided, as rhizomes may suffer from oxygen deprivation, potentially impacting growth and establishment (Mann et al.,

2013). Proper drainage is therefore recommended when growing MG in areas prone to standing water.

Compared to other biomass crops, MG has proven to be a superior performer in water-limited environments. Unlike maize, which suffers drastic yield reductions under drought stress, MG produces more biomass per unit of water consumed and has been successfully cultivated in arid and semi-arid regions (Plazek et al., 2014). Its low irrigation requirements make it a strong candidate for sustainable biomass production in areas facing water scarcity. Additionally, MG's deep root system enhances soil water retention, contributing to reduced erosion and improved hydrological balance in cultivated fields (Christian et al., 1997). Its natural leaf litter layer, formed by senesced leaves, helps reduce surface evaporation and increase moisture availability in the soil, further promoting water conservation in marginal lands (Caslin et al., 2010).

3.4.4. Fertilisation

MG is a low-input crop with minimal fertilisation requirements, so constitutes an interesting choice for biomass production (Christian et al., 1997). Unlike many other agricultural crops, MG efficiently recycles nutrients through its rhizome system, reducing the need for external fertilisation. During autumn senescence, the plant translocates essential nutrients, mainly nitrogen and potassium, from the above-ground biomass to the underground rhizomes, storing them for regrowth in the following season. This natural nutrient cycling minimizes nutrient losses and reduces environmental risks associated with fertiliser runoff and leaching (Caslin et al., 2010). The fertilisation needs of MG depend on factors such as soil type, previous land use, and cropping history. In well-fertile soils, particularly those with a history of agricultural use, fertilisation during the first two years is often unnecessary. Young MG plants have low nutrient uptake during their initial growth stages, meaning that applying fertilisers too early could stimulate weed competition rather than benefit the crop. However, as the plantation matures and biomass production increases, nutrient supplementation may be necessary to sustain productivity (Beale & Long 1997).

Studies indicate that mature MG plantations require approximately 60-100 kg ha^{-1} of N, 50-130 kg ha^{-1} of K, 7-15 kg ha^{-1} of P, and 3-12 kg ha^{-1} of Mg. Despite this, MG is highly efficient in nitrogen use, and excessive nitrogen application does not always lead to higher yields (Christian et al., 1997). In nutrient-rich soils or eutrophic peatlands, nitrogen fertilisation may not be necessary. In contrast, potassium uptake is typically high and should be prioritized in soils with low K availability, as it plays a crucial role in water regulation, biomass formation, and plant stress resistance (Beale et al., 1999). Phosphorus demand is significantly lower compared to nitrogen and potassium, meaning that most soils with moderate P availability can sustain MG without additional phosphorus inputs.

To reduce dependency on synthetic fertilisers, MG can benefit from organic fertilisation methods. Cattle slurry is an effective nutrient source, particularly from the third year onward, when MG has established its rhizome network and weed competition is reduced. To meet the annual phosphorus requirement of MG, approximately 28 cubic meters of cattle slurry per hectare can be applied. This

application would also supply 56 kg of nitrogen and 120 kg of potassium per hectare. However, applying livestock manure during the first two years is discouraged to prevent weed establishment (Caslin et al., 2010). From the second year onward, foliar fertilisers (including organic formulations) can be applied via drone technology or precision application methods to optimise nutrient uptake and biomass yields. This approach enhances efficiency while reducing environmental losses.

Unlike many high-input crops, MG has been shown to retain nitrogen efficiently in the rhizome system, reducing N losses to the environment. The recommended best practices for nitrogen management include avoiding N fertilisation in the first two years, as MG relies primarily on stored reserves and soil mineralization, applying N only in cases of nutrient depletion, using soil testing to assess needs, and limiting N application to ≤100 kg/ha, as excessive fertilisation does not significantly boost biomass yields but increases environmental risks such as nitrate leaching (Christian et al., 1997).

On the other hand, MG plays a critical role in soil restoration and nutrient cycling, contributing to long-term soil health. Its deep-rooting system improves soil structure, enhances water retention, and reduces erosion. Additionally, fallen leaves decompose naturally, returning organic matter to the soil and releasing nutrients for the next growing season (Caslin et al., 2010). By implementing site-specific fertilisation strategies, utilizing organic nutrient sources, and adopting precision application methods, farmers can maintain sustainable MG production while minimizing input costs and environmental impact (Pidlisnyuk et al., 2022; Bertola et al., 2024).

3.4.5. Pest management strategies

MG is highly resistant to pests and diseases, especially outside its native range in Asia, where most natural pests and pathogens are absent (Lewandowski et al., 2000). This innate resilience contributes to its low-input nature. Unlike many other agricultural species, MG typically does not require routine pesticide applications, further reducing production costs and ecological impact (Caslin et al., 2010). In Europe and North America, MG has not experienced major pest-related yield losses. However, as its commercial cultivation expands, native insects or newly introduced species may adapt to feeding on MG, posing a potential risk. One notable concern is the presence of moth larvae, which have been observed boring into stems. While they have not yet caused significant economic damage, continuous monitoring is essential to prevent future outbreaks. Fungal diseases are also not widespread in MG plantations. However, basal stem infections can occasionally occur, particularly in wet autumn or winter conditions. These infections may weaken stems, but they rarely result in significant biomass losses. MG's high lignin content and natural disease resistance contribute to its low susceptibility to fungal pathogens compared to other bioenergy crops (Christian et al., 1997).

While pest and disease threats are minimal, weed competition is a more significant concern, particularly during the establishment phase. In the first year, MG grows slowly, creating open spaces where weeds can compete for sunlight, nutrients, and water. If not managed properly, this competition can significantly hinder MG

establishment (Caslin et al., 2010). To mitigate this issue, proper ploughing and harrowing before planting help disrupt the weed seed bank, thereby reducing weed emergence. Furthermore, planting MG at the optimal time ensures strong early-season growth, allowing it to outcompete weeds more effectively (Christian et al., 1997). Additionally, applying a pre-emergence herbicide within two weeks after planting can help control annual weed species, further supporting MG's establishment. However, if weed pressure remains high, a post-emergence herbicide may be used selectively to target specific weed species. By the second or third year, MG forms a dense canopy that naturally suppresses weed growth. The leaf litter layer that accumulates over time further inhibits new weed germination by reducing light penetration to the soil surface (Caslin et al., 2010). From this point onward, weed control interventions become minimal or unnecessary.

3.4.6. Harvest timing and productivity

MG is a perennial crop that reaches its full biomass potential after an establishment period of three to five years (Lewandowski et al., 2000). Its annual growth cycle (**Figure 1)** follows a predictable pattern: during spring and summer, the plant undergoes rapid vegetative expansion and biomass accumulation. In autumn, it translocates nutrients from the above-ground biomass to the underground rhizomes, storing them for the next growing season (Christian et al., 1997). With the arrival of winter, the plant enters senescence and dries naturally, preparing for harvest. The timing of the harvest is crucial to maximising both biomass yield and quality. The optimal harvesting period for MG falls between late winter and early spring, typically between February and April, when stem moisture content decreases to around 15-20% (Caslin et al., 2010). Harvesting at this stage ensures that most nutrients have been transferred to the rhizomes, minimizing nutrient removal from the soil and enhancing the long-term sustainability of the plantation. If harvested too early, before February, the biomass retains a high moisture content, which complicates storage and reduces its combustion efficiency for bioenergy production (Lewandowski & Kicherer 1997). On the other hand, delaying harvest beyond April risks damaging new shoots emerging from the rhizomes, potentially reducing the yield of the next growing season.

Under favourable conditions, MG yields range between 20 and 35 dry tons per hectare per year (Pyter et al., 2009). In temperate regions of Southern Europe, such as Spain and Italy, yields typically range between 20 and 30 tons per hectare (Christian et al., 1997), while in Central and Northern Europe, they range from 10 to 25 tons per hectare due to lower temperatures (Beale & Long 1997). In the United States, the crop has demonstrated productivity levels of up to 35 tons per hectare in southern Illinois, with lower yields recorded in colder northern regions.

Harvesting is typically performed using conventional agricultural machinery adapted from forage and silage systems. There are two primary harvesting methods. The single-phase approach involves cutting, chopping, and collecting the crop in a single pass using a self-propelled forage harvester, which is ideal for bioenergy applications due to the ease of processing and transportation. The multi-phase method, on the other hand, involves mowing the crop first and allowing it to dry before baling or chipping for storage. This approach is often preferred for fibre

industries, animal bedding, and combustion applications where biomass integrity is essential (Caslin et al., 2010).

Post-harvest management plays a crucial role in maintaining biomass quality. To prevent degradation, baled biomass should be stored in dry conditions and protected from excess moisture. This is particularly important for biomass destined for bioenergy production, as its calorific value increases as moisture content decreases (Lewandowski & Kicherer, 1997). Proper storage and handling ensure that MG remains a high-quality, reliable feedstock for bioenergy, fibre industries, and other applications. By aligning harvest timing with optimal moisture conditions and implementing adequate storage practices, this crop maintains its reputation as a sustainable, high-yielding resource for renewable energy and industrial use.

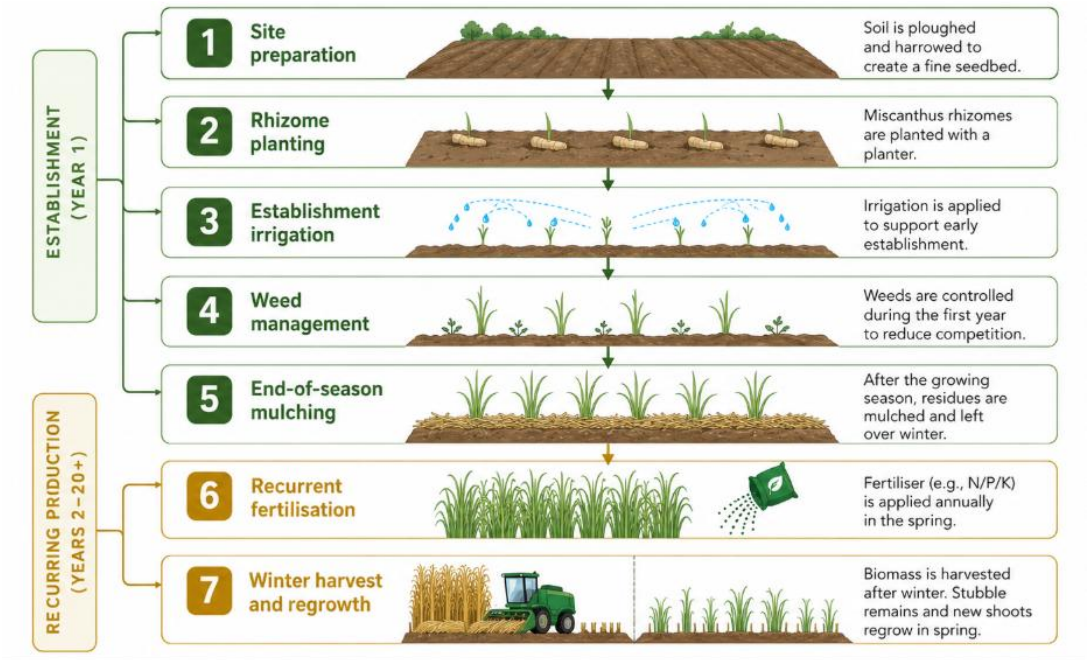

***Figure 1**. Original schematic representation of the Miscanthus × giganteus cultivation cycle, prepared by the pHYBi consortium to summarise the main establishment, growth, harvest and stand-management phases relevant to perennial biomass cultivation. The scheme is based on general agronomic information from Lewandowski et al. (2000), Christian et al. (1997), Caslin et al. (2010), Scordia et al. (2022) and Bertola et al. (2024).*

3.4.7. Sustainable cultivation practices

The cultivation of MG aligns well with sustainable agricultural practices due to its ability to grow with minimal inputs while providing significant environmental benefits (Lewandowski et al., 2000). By implementing specific low-impact management strategies, farmers can optimise biomass yields, maintain soil health, and minimize ecological disruption.

Minimal fertilisation and nutrient recycling. One of the most sustainable aspects of MG is its efficient internal nutrient recycling system, which reduces the need for external fertilisation (Christian et al., 1997). During the senescence phase in autumn, the plant translocates essential nutrients like nitrogen and potassium from its above-ground biomass to the underground rhizomes. This allows the stored nutrients to be reused in the following growing season, decreasing fertiliser dependency (Caslin et al., 2010). To further minimize synthetic fertiliser use, organic soil amendments such as compost or cattle slurry can be applied, but only from the third year onward to avoid promoting weed growth in the early establishment phase. Additionally, periodic soil testing can help adjust fertilisation strategies to meet site-specific nutrient demands without over-application, preventing runoff and soil degradation.

Efficient weed management without long-term herbicide use. Weed control is crucial during the first two years of MG establishment, as the crop grows slowly at the beginning, leaving room for competition. Instead of relying heavily on herbicides, sustainable management focuses on pre-planting soil preparation, mechanical cultivation, and strategic planting timing to reduce weed pressure naturally. After the second or third year, MG's dense canopy shades the soil, significantly reducing weed germination and eliminating the need for chemical herbicides. Farmers can further suppress weeds by using mulch from the crop's own senesced leaves, which form a natural protective layer on the soil. This approach reduces chemical input costs and enhances soil health by promoting organic matter accumulation (Lewandowski et al., 1997).

Water conservation and drought resilience. MG is highly efficient in water use, thanks to its deep-rooting system that allows it to access moisture from lower soil layers. In most regions with moderate rainfall (600–800 mm annually), MG can grow without supplemental irrigation. Sustainable water management practices include: selecting planting sites with good natural drainage to avoid waterlogging while maximising water retention; implementing cover cropping or maintaining surface residues to reduce evaporation and improve water infiltration; avoiding irrigation except in extreme drought conditions or during the initial establishment phase in arid regions; and by minimizing water inputs and improving soil water retention, MG remains a viable option for sustainable biomass production in water-scarce environments (Beale & Long, 1997).

Carbon sequestration and soil regeneration. MG plays a significant role in climate change mitigation by acting as a powerful carbon sink. Its perennial nature and extensive root system promote soil carbon sequestration, helping to store atmospheric carbon within the soil and reducing greenhouse gas emissions. Unlike annual crops that require frequent tillage, MG cultivation enhances long-term soil structure, prevents erosion, and increases organic matter accumulation. To further improve soil health, farmers can adopt no-till or reduced-till planting methods, allowing MG rhizomes to establish without unnecessary soil disturbance. Additionally, integrating MG into crop rotation systems with other perennial species can help diversify soil microbial activity and restore degraded lands.

Biodiversity enhancement and habitat creation. Beyond its agronomic benefits, MG plantations contribute positively to biodiversity by creating habitats for various

wildlife species. The tall, dense structure of MG fields provides shelter for birds, small mammals, and beneficial insects, promoting ecological balance in agricultural landscapes. To maximise biodiversity benefits, sustainable practices include designing MG plantations with buffer zones that integrate native vegetation or wildflower strips; reducing harvest frequency in some areas to allow wildlife refuge during breeding seasons; and minimizing chemical inputs to protect pollinators and soil organisms essential for a healthy ecosystem.

3.5. HEMP

3.5.1. General overview

The cannabis plant (*Cannabis sativa* L.) is one of the world's oldest crops, which has been widely cultivated due to its industrial, nutritional, medicinal, and psychotropic products. The multifunctional hemp's abundance of beneficial ecological, agronomical, and pharmaceutical properties qualifies it as a useful raw material for a variety of conventional (fibre, food, oil, medicine) and advanced industrial products (Bernstein & Gorelick, 2020). Hemp is unusual in that it may be used to produce a wide range of products. It has traditionally been grown for fibre or as a crop with two uses (both grain and fibre). It is widely regarded as a crop with various uses and a wide range of current and future applications, including those for nutrition, energy, textiles, healthcare, and a wide range of industrial goods (Caplan & Matzneller, 2022; Rheay et al., 2021; Scalabrin et al., 2024). The main characteristics of hemp are detailed in **Table 3.5.**

Table 3.5. General morphology and characteristics of hemp.

Morphology and growth characteristics	
Family	Cannabaceae
Life form	Herbaceous flowering plant
Main use	Oil production, textile applications and pulp and paper production
Used plant part	Above-ground biomass
Growth habit	Annual plant with a spindly main stalk covered with leaves
Height	Over 2.5 meters with long, straight stalk
Stem	Green, cylindrical stem with a woody interior
Leaves	Fan-shaped, palmate, and deeply lobed, with 5-7 lobes and serrated edges
Inflorescence	The flowering structures, develop at the apical part of the main, second, and third-order branches in female plants, while male plants accumulate flowers on the upper part of the central stem

Choosing the appropriate hemp variety is a crucial step in ensuring successful and cost-effective cultivation, particularly when hemp is considered for marginal land or phytomanagement purposes (Blandinières and Amaducci, 2022; Scalabrin et al., 2024). In this context, cultivar choice should not be based only on end use, but also on establishment capacity, tolerance to salinity or drought, response to

contaminated soils, biomass quality and restrictions associated with contaminant uptake. Since C. sativa is grown for three primary purposes (fibre, seed, and cannabinoid (CBD) production) each end-use requires cultivars with specific morphological, chemical, and agronomic traits.

- Varieties for fibre production should be tall (over 2.5 meters) with long, straight stalks, low in lateral branching and rich in bast fibre content and, genetically predisposed to early flowering to maximise stem growth (Example varieties: Futura 75, Santhica 27, Bialobrzeskie). According to Amaducci et al., (2020), fibre cultivars with over 30% bast fibre content in the stem offer the best balance of quality and industrial yield for textile, construction, and biocomposite applications.
- Seed-oriented cultivars are characterised by short to medium height (1.5–2.5 meters) to allow easier harvesting, a short vegetative cycle (less than 120 days) and, high seed yield (over 1 ton/ha) and oil content of up to 35% (Example varieties: Finola (Finland), Fasamo, Fedora 17). These cultivars are typically monoecious (having both male and female flowers on the same plant) to promote uniform flowering and simplify mechanical harvesting and processing (Ferfuia et al., 2020).
- CBD cultivars should have dense, resinous flowers rich in glandular trichomes, high CBD content and minimal THC concentration (below 0.3%), a stable chemotype with a CBD:THC ratio often exceeding 20:1 and, suitability for harvest before cannabinoid degradation or THC exceedance (Example varieties: Tiborszallasi, Carmagnola, Earlina 8 FC). As noted by Mishchenko et al., (2022), the genetic profile of each cultivar (e.g., presence of CBDA synthase) should be verified via lab testing, as environmental factors may influence cannabinoid expression, even within the same variety. For phytomanagement on marginal, contaminated or salt-affected soils, these end-use categories should therefore be combined with a second selection filter based on stress tolerance. Fibre-oriented cultivars may be preferable where stem biomass and textile valorisation are the main objectives, but their use should depend on germination, establishment, salinity response, contaminant uptake and the suitability of harvested biomass for safe non-food applications.

The cultivation of industrial hemp is subject to strict legal frameworks in most countries around the world. For legal and successful production, it is essential to have a thorough understanding of the local regulatory environment, licensing systems, and the chemical composition requirements of the plant, particularly the tetrahydrocannabinol (THC) content. This compound, which is psychoactive, represents the most important legal criterion in hemp cultivation, as its concentration is strictly limited by law. In the European Union, the legal THC threshold in hemp plants is ≤ 0.3% (previously 0.2%). Only certified varieties listed in the EU Common Catalogue are permitted for cultivation. These varieties are genetically stable and proven to contain low levels of THC. Growers must retain seed certification documentation and labels as proof of legal compliance. Depending on the country, growers are required to (i) register their hemp cultivation areas with the relevant agricultural authorities; (ii) declare planting intentions and field

locations within a specified deadline; and (iii) allow sampling and THC testing before harvest, conducted by authorized inspectors or certified laboratories.

In some jurisdictions (e.g., for CBD product production), additional registration is required for processing activities under food safety or pharmaceutical regulations. Failure to comply may result in crop destruction, loss of license, or financial penalties. For all products derived from industrial hemp (CBD oils, hemp protein, fibre, cosmetics), producers must (i) adhere to Good Manufacturing Practices (GMP) and GACP standards when applicable; (ii) provide lab-tested THC/CBD concentration certificates for each product batch, and, (iii) ensure full traceability from seed to shelf, often using digital tracking systems or QR-coded labelling.

3.5.2. Climatic conditions

Hemp is considered a thermophilic crop, with a minimum germination temperature of 1–3 °C. However, optimal growth and development occur within a daily temperature range of 15 to 27 °C. When temperatures exceed 30 °C, photosynthesis may slow down, and fibre quality may decline, especially under water-deficient conditions. Sufficient rainfall during the first six weeks of growth is critical, as this period is characterised by intensive vegetative development. In areas where total seasonal rainfall falls below 400 mm, supplemental irrigation is advised, particularly in regions with hot and dry summers. However, excessive moisture, especially in poorly drained soils, can favour the development of pathogens such as *Botrytis cinerea*, significantly affecting both yield and quality. In addition to temperature and precipitation, photoperiodism also plays a crucial role in hemp cultivation. As a short-day plant, *C. sativa* may initiate flowering prematurely if exposed to shortened daylight periods too early, limiting vegetative growth and fibre production.

3.5.3. Water requirements

Water management is a key factor influencing the growth, yield, and quality of hemp, especially in regions with variable or limited precipitation. Hemp is moderately drought-tolerant but particularly sensitive to both waterlogging and water stress during critical growth stages such as germination, establishment, and early vegetative development.

During the germination and seedling stages, moderate but consistent soil moisture is essential for uniform emergence and early root development. Water stress at this stage can significantly reduce plant establishment and ultimately lower yields. According to Cosentino et al., (2012), optimal soil moisture in the top 10 cm is required for proper germination, particularly in soils with low capillarity. In later growth stages, hemp develops a deep taproot system (up to 2.5 m), allowing it to access deeper moisture reserves. However, prolonged drought during flowering and seed set stages can negatively affect cannabinoid biosynthesis (in CBD hemp) or seed filling (in grain hemp).

In addition, hemp is extremely sensitive to waterlogging, especially in compacted or poorly drained soils. Water saturation leads to oxygen depletion in the root zone, resulting in root hypoxia, stunted growth, and increased susceptibility to root-borne pathogens such as Pythium and Fusarium. Struik & Amaducci (2000) emphasize

that even short periods of excess moisture can reduce stem elongation and fibre quality.

Therefore, in dry or semi-arid climates, irrigation is recommended to maintain adequate soil moisture levels. Drip irrigation is preferred in CBD hemp production due to its precision and ability to target individual plants. It minimizes water loss through evaporation and helps prevent fungal issues by avoiding wetting of foliage. On the other hand, sprinkler systems may be used for fibre or seed hemp in larger fields, especially during early growth stages. However, these systems can increase relative humidity and risk of foliar diseases if not managed carefully. Amaducci et al., (2008) report that supplemental irrigation during the early vegetative phase (approximately 4–6 weeks after sowing) can significantly increase biomass accumulation and plant uniformity, particularly under Mediterranean and continental climates.

Irrigation scheduling should be based on (i) soil moisture sensors, (ii) weather data (ET_0 models) and (iii) visual indicators (wilting, leaf angle changes). Maintaining soil water content between 60–80% of field capacity is ideal during the vegetative stage. Over-irrigation must be avoided at all times, particularly in clay soils with poor infiltration capacity.

3.5.4. Fertilisation

Optimal fertilisation of hemp is essential to support vigorous vegetative growth, biomass accumulation, and high-quality yield, be it for fibre, seed, or cannabinoids. Nutrient management should always begin with a soil test to evaluate baseline fertility and tailor fertilisation strategies accordingly.

Before any fertiliser is applied, a comprehensive soil analysis is highly recommended to assess nutrient availability, organic matter content, and pH levels. This allows for precise calibration of nitrogen (N), phosphorus (P), and potassium (K) inputs and prevents over- or under-application, which can lead to nutrient deficiencies or environmental leaching. Phosphorus and potassium levels should be corrected before sowing, while nitrogen can be applied in split doses during the growing season. Research shows that the form, timing, and placement of nutrients significantly influence plant uptake and performance (Kaur et al., 2023).

Based on agronomic trials in various regions, general nutrient recommendations for industrial hemp are:

- Nitrogen (100–150 kg/ha): promotes vegetative growth, particularly important for fibre production. Excess N in CBD varieties may lead to excessive leaf biomass and reduced cannabinoid concentration. Nitrogen should be split, with 60–70% applied at planting and the remainder during early vegetative growth (around 3–5 weeks after emergence). Slow-release or stabilized nitrogen sources are recommended to prevent leaching and volatilization (Ahmadi et al., 2024).
- Phosphorus (50–80 kg/ha): essential for root development, early plant vigour, and seed formation. However, research indicates that over-application of phosphorus does not necessarily improve yield or quality (Westmoreland & Bugbee, 2022).

- Potassium (80–120 kg/ha): supports water regulation, enzyme activation, and stress tolerance. Particularly important under drought-prone conditions.

Additionally, both organic and mineral fertilisation programs can be effective, depending on the production system. Organic inputs such as compost, digestate, and manure enhance soil structure and stimulate microbial activity, contributing to long-term soil health. In contrast, mineral fertilisers offer precise and readily available nutrients, but their application requires careful scheduling to avoid nutrient losses and ensure optimal plant uptake. Integrated systems combining both approaches (e.g., compost plus foliar N) can enhance long-term soil fertility while supporting immediate plant needs (Massuela et al., 2023).

Fertilisers should be incorporated into the soil prior to planting for uniform availability. In high-value CBD hemp, localized fertigation via drip irrigation can increase nutrient use efficiency. For larger-scale fibre and seed production, broadcast or band application methods are preferred. Regular tissue testing during the growing season can further guide in-season nutrient adjustments.

C. sativa thrives best in well-drained, humus-rich soils of medium texture, such as sandy loam or loamy soils. The ideal soil pH ranges between 6.0 and 7.5, which ensures optimal availability of essential macro- and micronutrients like nitrogen (N), phosphorus (P), and potassium (K). A deficiency of these elements can result in stunted vegetative growth and reduced fibre or seed yield, depending on the hemp variety. It is strongly recommended to conduct an agrochemical soil analysis at least two weeks before sowing to determine the need for soil amendments or fertilisation. According to Campiglia et al., (2017), the application of compost or well-rotted manure significantly improves soil structure and microbial activity, promoting root development and plant health. Soils with high compaction or poor drainage should be avoided, as they increase the risk of anoxic conditions in the root zone, negatively affecting plant metabolism and possibly causing root rot.

3.5.5. Pest management strategies

Hemp is known for its rapid early growth and competitive canopy structure, which provides effective natural weed suppression. However, weed and pest management are still critical, particularly during the early growth stages. Improper management can significantly reduce yields, quality, and plant health, especially in CBD and seed hemp production systems.

Although generally resilient, hemp can be affected by a range of insect pests. The most common include aphids (*Myzus persicae, Aphis fabae*), which feed on sap, reducing plant vigour and transmitting viral diseases; caterpillars (Spodoptera spp., Helicoverpa spp.), which consume leaves and floral tissues; spider mites (*Tetranychus urticae*), particularly prevalent in indoor or dry conditions, causing chlorosis and webbing on leaves; and thrips, which damage young tissues and can act as vectors for viruses. Integrated pest management strategies include biological control using natural predators such as lady beetles (Coccinellidae), lacewings (Chrysopidae), and parasitic wasps; the application of botanical insecticides like neem oil or microbial agents such as *Beauveria bassiana* and *Bacillus thuringiensis*;

and mechanical methods, including netting and the use of trap crops to divert pests away from hemp plants.

In addition to insect pests, hemp is also susceptible to several fungal diseases that can impact plant health and yield. Common issues include powdery mildew (Golovinomyces sp.), which presents as a white powdery coating on leaves and can interfere with photosynthesis; downy mildew, which thrives in humid environments and requires early detection and the use of resistant cultivars; and root rot caused by pathogens such as Pythium and Fusarium, often linked to poorly drained soils. Effective disease management in hemp relies on integrated practices, including maintaining good air circulation through proper plant spacing, avoiding over-irrigation and waterlogging, and implementing crop rotation to reduce the buildup of soil-borne pathogens.

During the first 3–5 weeks after germination, hemp seedlings are vulnerable to competition from annual and perennial weeds, especially in wider row spacing systems such as those used for seed and CBD hemp. Studies (Struik & Amaducci, 2000) indicate that even moderate weed pressure during early growth can reduce biomass yield by up to 40%. Mechanical cultivation (rotary hoeing, shallow tillage) is effective in conventional systems when weeds are small. Organic mulching (e.g., straw, compost, or biodegradable plastic mulch) suppresses weed germination by limiting light and stabilizing soil moisture, particularly in CBD hemp fields where mechanical weeding is impractical. In no-till or organic systems, cover cropping and crop rotation with weed-suppressive species (like rye or buckwheat) is also a valuable strategy for pre-plant weed control (Carrubba et al., 2015).

3.5.6. Harvest timing and productivity

Optimal harvest timing is crucial to preserve the quality and yield of hemp crops, especially since the plant is cultivated for distinctly different end-uses: fibre, seed, or CBD-rich flowers. Each purpose requires precise identification of physiological maturity, as well as appropriate harvesting equipment and post-harvest handling techniques.

3.5.6.1. Fibre Hemp

Hemp grown for fibre is typically harvested at the onset of full flowering (approximately 75% flowering stage). This developmental phase ensures that the primary bast fibres have reached maximum elongation and flexibility, while avoiding excessive lignification of the core. If harvested too early, fibre yield is low, and bast fibres may be immature and weak. If harvested too late, fibres become coarse, brittle, and less suitable for textile applications (Amaducci et al., 2015). The most common method for harvesting fibre hemp is mower-conditioning, followed by field retting, where the stems decompose slightly to separate the bast from the hurd. After harvest, hemp stalks must undergo retting, a microbial process that breaks down the pectins binding the bast fibres to the woody core (hurd).

There are several types of retting used to extract fibres from plant stalks. Field retting, also known as dew retting, is the most common method. It involves leaving the stalks in the field for 3 to 6 weeks, depending on the climate, and requires

regular turning to ensure uniform microbial breakdown. Water retting is a faster and more controlled process, typically taking 7 to 10 days, and is carried out in tanks or slow-moving water; however, it generates wastewater that must be treated. Enzymatic retting is a more sustainable and faster alternative currently under development, though it remains relatively expensive.

Once retted, stalks are dried and then decorticated, a mechanical process that separates bast fibres from the inner hurd. Decortication efficiency depends on retting quality, harvest timing, and moisture content. The extracted fibre is further cleaned, carded, and processed depending on its final use (e.g., textiles, bioplastics, insulation).

3.5.6.2. Seed Hemp

Seed maturity is reached when seed colour has darkened, seed coat is hardened and, 60–80% of seeds are firm and not green or soft. Harvesting must occur just before natural seed shattering begins, to prevent loss. Mechanical harvesters similar to those used for grain (e.g., combine harvesters with modified headers) are commonly employed. According to Zheljazkov et al. (2023), harvesting too late increases seed loss due to shattering and pod dehiscence, especially under windy or dry conditions. Post-harvest drying is essential to reduce moisture below 10% to preserve seed viability and oil quality.

Immediately after harvest, hemp seeds must be carefully handled to ensure quality and viability. They are first cleaned using air screen cleaners to remove chaff, dirt, and plant fragments. Following cleaning, the seeds must be dried to a safe storage moisture content of 9% or less to prevent mold growth, rancidity, and loss of germination potential. This drying process is typically carried out using ambient air or slightly heated air at temperatures below 40°C. High-value seed lots are often tested for germination rate, oil content, and impurities. Storage in airtight, cool conditions preserves seed viability and maintains nutritional and functional quality.

3.5.6.3. CBD Hemp (Floral Biomass)

CBD-rich hemp is harvested when trichomes (glandular hairs) on the flowers turn from clear to cloudy/milky, indicating peak cannabinoid concentration. This usually occurs from late summer to early fall, depending on the cultivar and latitude. Delaying harvest beyond this window risks cannabinoid degradation (CBD to CBN conversion) and mold development. Frequent laboratory testing of cannabinoid content is recommended in the weeks leading up to harvest to time it accurately and comply with legal THC limits.

Harvesting methods for hemp vary depending on the scale of production. Small-scale farms often rely on hand harvesting to preserve the integrity of the flowers. In contrast, large-scale CBD operations use modified tobacco harvesters or stripping machines, followed by immediate drying at controlled temperatures below 35°C to retain valuable terpenes and cannabinoids (Massuela et al., 2022). Once harvested, CBD-rich floral material requires prompt processing to maintain its chemical profile. The drying process is conducted in low-light, low-humidity environments with gentle airflow, ideally at temperatures between 30 and 35°C, and typically lasts 5 to 10 days depending on flower density and environmental conditions. After drying,

the buds undergo curing by being stored in sealed containers for 1 to 3 weeks, allowing chlorophyll to break down and flavours to stabilize. During this phase, humidity is maintained around 60%, with daily ventilation to prevent mold formation. Finally, the extraction stage involves using solvents such as ethanol or supercritical CO_2 to obtain concentrates like full-spectrum oil, distillate, or isolate. All extraction processes must comply with Good Manufacturing Practices (GMP) and local regulations, particularly concerning residual solvents and THC content.

3.5.7. Sustainable cultivation practices

Optimal planting practices are essential for ensuring high yields and consistent quality in hemp production, whether cultivated for fibre, seed, or CBD. Key parameters such as planting time, seeding rate, depth, and row spacing must be adjusted according to the specific production objective and local agro-climatic conditions.

Hemp should be sown in late spring when the soil has warmed to a minimum of 10°C, which supports rapid and uniform germination. Optimal sowing temperatures lie between 12°C and 16°C, with the best emergence observed when daily mean air temperatures remain stable above 13°C. According to Tang et al. (2017), early planting (late April to early May in temperate climates) allows the crop to capitalize on the full vegetative growth phase before the onset of flowering, especially important for fibre varieties. In contrast, delayed sowing can limit plant height and biomass accumulation, particularly if flowering is triggered by shortening photoperiods.

Seeding density directly influences plant architecture, canopy closure, and yield components:

- Fibre production requires high plant density (50–70 kg/ha) to promote stem elongation and reduce lateral branching. Dense stands minimize weed pressure by creating a fast-closing canopy
- Seed production benefits from lower seeding rates (25–35 kg/ha), allowing better light penetration and air circulation, which enhances pollination efficiency and seed maturation
- CBD-rich hemp (female plants only) requires individual plant management. It is typically planted at very low densities (1–2 meters between plants) to support extensive lateral branching and floral development. This spacing also facilitates mechanized harvesting and reduces disease pressure.

Campiglia et al. (2017) found that reducing seeding rate in CBD hemp cultivation significantly improves cannabinoid concentrations due to better resource allocation per plant.

Seeds of *C. sativa* are relatively large and should be sown at a depth of 2–3 cm, depending on soil type and moisture conditions. In lighter (sandy) soils, deeper sowing may be necessary, while in heavier (clay) soils, shallow sowing is preferable to avoid seed rot. Uneven planting depth can cause irregular emergence and reduced stand uniformity. Row spacing is adjusted according to cultivation goals:

- Fibre hemp is sown in narrow rows (15–20 cm) to encourage vertical growth and straight stems, resulting in longer bast fibres
- Seed hemp requires wider row spacing (60–90 cm), enabling better access to light and airflow, both crucial for seed maturation and disease prevention
- CBD hemp is often planted with inter-row and intra-row spacing of 1–2 meters. This configuration provides sufficient space for plant development and facilitates manual pruning, inspection, and targeted harvesting.

Struik & Amaducci (2000) emphasize that spacing is a key determinant of canopy structure, which in turn influences microclimate, pest dynamics, and resource competition.

Effective record-keeping is a fundamental component of sustainable and compliant hemp cultivation. Monitoring and documenting each stage of production not only supports regulatory adherence, especially in the context of cannabinoid content, but also enables farmers to refine practices over time, optimise inputs, and increase profitability.

Integrated Pest Management (IPM): is a holistic approach that combines cultural, mechanical, biological, and chemical controls based on regular field scouting. In hemp, effective IPM involves:

- monitoring with yellow sticky traps or direct inspection,
- threshold-based intervention – treating only when pest levels surpass economic thresholds,
- resistant cultivars – where available for specific pathogens,
- preventive action – maintaining plant health through balanced nutrition and irrigation.

Hemp growers are advised to maintain structured and timely records to ensure compliance, traceability, and optimal crop performance. Key data to log include planting and harvest dates to monitor phenological stages and improve scheduling, as well as seed source and variety, which is critical when cultivating licensed CBD cultivars. Detailed records of soil analysis (such as pH, organic matter, and nutrient or fertiliser applications) help guide soil management. Irrigation events, including method, timing, and quantity, are important for water efficiency and cannabinoid production. Pesticide or biological treatments must also be documented, including active ingredients and application rates, to meet food safety and legal requirements. Weather events like rainfall, frost, or extreme heat should be noted, as they can affect plant development and cannabinoid profiles. Yield data (covering fresh and dry biomass, cannabinoid content, and seed or oil output) along with THC compliance testing results, are essential for regulatory adherence, particularly in jurisdictions where THC must remain below 0.3%.

These records support Good Agricultural and Collection Practices (GACP) and Good Manufacturing Practices (GMP), especially for CBD production intended for extraction. Modern hemp operations increasingly use farm management software (e.g., Trimble Ag, Agrivi, Cannavigia), blockchain-based traceability platforms, and

QR-coded plant passports in regulated markets to enable real-time monitoring and streamline certification audits. In many countries, growers must also submit mandatory reports to government agencies, including planting intentions, pre-harvest THC test results, and destruction reports for non-compliant crops. Failure to maintain adequate documentation can result in fines, license revocation, or product seizure. Conversely, well-documented farms are better positioned to access subsidies, achieve certifications (e.g., organic, GMP), and secure commercial contracts (Caplan et al., 2022).

The literature indicates that hemp has potential for phytomanagement and biomass production on selected marginal lands, but its suitability is highly dependent on cultivar, soil constraint and final biomass use (Blandinières and Amaducci, 2022; Placido and Lee, 2022; Scalabrin et al., 2024). Hemp may tolerate some heavy-metal-contaminated soils, although contaminant uptake can restrict subsequent biomass valorisation routes (Placido and Lee, 2022; Rheay et al., 2021). In contrast, salinity, poor soil structure and drought can strongly affect establishment and productivity. For pHYBi, hemp is therefore considered a conditional candidate crop for selected low-to-moderate stress conditions, particularly where establishment can be supported through organic amendments, irrigation control or microbial inoculation (Blandinières and Amaducci, 2022; Ahmadi et al., 2024; Scalabrin et al., 2024)

4. CONCLUSIONS AND NEXT STEPS

D2.1 provides an evidence base for selecting, prioritising and managing the lignocellulosic crop portfolio defined for pHYBi under the marginality constraints addressed in the project. The analysis should therefore be understood as a project-specific suitability assessment rather than as a global ranking of all possible phytoremediation crops. It confirms that no crop is universally suitable for all marginal soils. Instead, phytomanagement strategies must be designed as integrated crop × genotype/cultivar × soil constraint × treatment × monitoring packages.

For metal-contaminated soils, the most relevant evidence supports the prioritisation of woody species, especially poplar and willow, with genotype or clone selection as a key determinant of performance. For hydrocarbon-affected and mixed-contamination soils, miscanthus appears as the most robust operational candidate among the materials currently considered in pHYBi, while hemp should be retained only for low-to-moderate stress conditions or where establishment can be supported through amendments and microbial inoculants. For saline soils, the literature and the first WP2 results indicate that crop choice must be conservative and linked to measured salinity levels, water management, soil amendments and microbial support. Based on this evidence, the following integrated management packages are proposed to convert the crop-specific recommendations into overall phytomanagement strategies for the main marginality constraints addressed in pHYBi.

Table 4.1. Integrated phytomanagement strategy packages for marginal, contaminated and saline land

Marginality constraint	Objective/ Priority crops or material	Integrated strategy/ Monitoring criteria
Metal-contaminated soils	Objective: phytoextraction and/or phytostabilisation, depending on metal mobility and biomass-use restrictions. / Priority material: poplar and willow as benchmark woody crops; birch as complementary stabilisation species.	Select suitable clones/genotypes according to establishment, biomass production and contaminant partitioning. Use site-adapted planting density, short-rotation coppice where biomass removal is required, and amendments only where needed. / Monitor: survival, biomass, soil pH, available metal fractions, root/shoot metal partitioning and biomass safety.
Hydrocarbon-affected or mixed-contamination soils	Objective: rhizodegradation, soil biological activation, erosion control and biomass production/ Priority material: Miscanthus; hemp only under low-to-moderate stress; poplar where woody systems are suitable.	Maintain perennial cover to stimulate the rhizosphere and stabilise soil. Combine establishment support, organic amendments and microbial inoculants where appropriate. Avoid excessive fertilisation or irrigation that may mobilise contaminants/ Monitor: establishment, biomass, soil organic carbon, microbial activity, contaminant dissipation, phytotoxicity and biomass quality.
Saline or salt-affected	Objective: salinity-tolerant biomass production, soil cover	Use measured salinity levels to decide crop suitability. Prioritise establishment support,

agricultural soils	and soil-structure improvement/ Priority material: Miscanthus × giganteus as operational reference; hemp only after tolerance screening.	irrigation management, organic matter inputs and saline-adapted microbial inoculants. Avoid cultivation where salinity prevents establishment/ Monitor: electrical conductivity, soil moisture, emergence, survival, biomass, salt-stress symptoms and salinity trends.
Low-fertility or degraded marginal land	Objective: soil cover, biomass production, soil organic matter recovery and erosion control/ Priority material: Miscanthus, poplar, willow or birch depending on soil depth, water availability and land-use constraints.	Select low-input perennial crops and adapt fertilisation to soil nutrient status. Use organic amendments, mulching and reduced soil disturbance to support establishment and soil recovery/ Monitor: establishment, biomass, soil organic carbon, nutrients, erosion risk, water availability and stand persistence.

These strategy packages are intended to guide the transition from general crop management recommendations to site-specific phytomanagement implementation. Final decisions for each case study will depend on soil characterisation, crop tolerance testing, amendment and microbial optimisation, biomass safety assessment and the feasibility of the targeted bio-based value chain.

Building on this foundation, the next steps of the pHYBi project will advance towards the validation and practical optimisation of the selected cropping strategies for phytomanagement on marginal soils. In tasks 2.2 and 2.3, experiments will be carried out under controlled conditions (greenhouse or bench-scale) to evaluate the tolerance of the crops to contaminants, as well as the interaction between plant species, microbial consortia and amendments (organic and inorganic), in order to optimise biomass production and phytoremediation capacity. These trials will be conducted by several project partners using soils representative of the case studies, and will allow for the analysis of agronomic and physiological crop performance under different types of stress (metal or organic contamination, salinity, low fertility). Subsequently, in task 2.5, the selected strategies will be validated through the installation of on-site pilot field trials in different European regions, to assess their performance, adaptability and pre-commercial viability (TRL 5). These plots will allow an integrated evaluation of the effects of the management strategies on agronomic parameters (biomass production, vigour, root development), physicochemical parameters (pH, nutrient content, organic carbon, salinity), and microbiological indicators (diversity and activity of soil and rhizosphere microbiota).

In parallel, work packages WP4 and WP5 will complement these experimental actions with modelling tools, integrated evaluation and sustainability analysis. WP4 will develop a virtual replication tool based on mathematical models and experimental data, allowing simulation of the impact of different cropping and valorisation strategies in multiple agroecological scenarios, facilitating their transfer to other territories. This tool will integrate soil models, crop yield, phytoremediation efficiency and biomass quality, connecting field processes with industrial valorisation outcomes. In turn, WP5 will carry out a holistic assessment of the performance of the implemented strategies, including environmental life

cycle assessment, life cycle cost analysis, and evaluation of social impact through the Social-LCA methodology. This integration will help identify critical points, compare technological routes, and establish guidelines for safe, equitable and economically viable implementation. In addition, the ecosystem co-benefits generated by the crops will be evaluated, such as improvements in soil health, carbon sequestration, functional biodiversity and climate resilience.

Altogether, this deliverable represents a key milestone in building the technical knowledge needed for the deployment of cropping strategies aimed at phytomanagement of degraded soils. It provides a solid scientific basis for the implementation and validation of nature-based solutions, with high potential for replication and alignment with European priorities in sustainability, soil restoration and circular bioeconomy. The next steps of the project will transform this knowledge into concrete interventions on the ground, generating measurable impact evidence and valuable insights for transfer to other territories and productive sectors beyond the experimental scope.

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