PAPER • **OPEN ACCESS**

Upscaling bio-based products: poplar and hemp for soil and building circular synergies

IOP Conf. Series: Earth and Environmental Science **1402** (2024) 012033 doi:10.1088/1755-1315/1402/1/012033

Upscaling bio-based products: poplar and hemp for soil and building circular synergies

Elisa Zatta[1,*], Elena Ferraioli[1], and Elisa Bernard[1]

[1] Iuav University of Venice, Department of Architecture and Arts, Santa Croce 191, 30123, Venezia, Italy

*Corresponding author: elisa.zatta@iuav.it

Abstract. The paper illustrates the rationale of an ongoing research aimed at identifying innovative applications for poplar- and hemp-based products in constructive systems, focusing on load-bearing poplar plywood elements and hemp blocks and panels for the building envelope. The underlying approach extends the circular-based perspective from the building component scale to the territorial and economic one, adopting a context-wise approach. The potential of these renewable materials is examined beyond the application to reversible building systems, to depict their comprehensive contribution to a carbon-neutral region by examining the links with the local territorial management and a potential short supply chain. The contribution describes poplar and hemp agricultural productions, connecting their outputs to several economic sector. After addressing the environmental benefits, the two cultivations produce in terms of climate change mitigation and adaptation, among which carbon uptake, it contextualises poplar- and hemp-based products within current bio-based solutions in the building sector, exploring possible applications in new and existing constructions through circular constructive systems. The results discussion outlines the sustainable multiscale synergies supported by poplar- and hemp-based building products within the research perimeter.

Keywords: multi-scale approach, low-carbon building systems, renewable materials, soil management and regeneration, reversible construction.

1. Introduction

In line with global institutional frameworks, European strategies have been increasingly highlighting the importance of a shift towards circularity in all the energy and carbon-intensive sectors, among them construction [1] [2]. In this context, policy trajectories stress the need to go beyond the actions targeting the buildings' operational life and to adopt of a whole life carbon perspective, defined as the one encompassing "all greenhouse gas emissions resulting from the materials, construction and the use of a building over its entire life, including its demolition and disposal. It is thus the total amount of embodied and operational emissions" [3]. Several strategies can be jointly undertaken to support carbon neutrality in construction; at a global scale, the United Nations Environmental Programme (UNEP) summarises them in three urgent pathways [4]:

- Building (with) less and improving circularity.
- Shifting to bio-based building materials.
- Decarbonising conventional materials and only using non-renewable, carbon-intensive, extractive materials when absolutely necessary.

Nevertheless, when transposing these strategies to different geographical and economic contexts such as the Italian North-East one - on which the paper focuses - they have to be tailored depending on the specific construction sector, built environment, and territory.

Nowadays, the Italian building practice is tied to consolidated techniques and materials, distinguished by concrete and masonry blocks structures, a circumstance hindering the improvements towards the circular management of actual and future built resources. In fact, when a building reaches its end of life, the reclamation of the structural elements is unlikely an option and the selective demolition results in large, underused quantities of construction and demolition waste. Given that the allowed percentage of recycled aggregate for the structural parts is significantly limited [5], concrete is generally downcycled, as it happens for the masonry components. Hence, considering the energy-intensive nature of these conventional building materials, material efficiency and material substitution appear to be the most effective strategies to prevent significant carbon lock-in paths in the built environment [6]. The depicted scenario highlights the need to investigate structural reversible building systems, especially the ones making use of non-extractive and renewable materials.

In Italy, the building stock is extensively heterogeneous in terms of age distribution [7]; most of it currently requires functional and, above all, energy retrofit, an urgency underlined also by European strategies [8]. Recent economic incentives have encouraged privates to improve the energy efficiency of the residential buildings' envelope and installations, however a large share of the whole stock still proves to be unfit [9]. Therefore, solutions for the energy efficiency of the building envelope in both future and existing buildings must be investigated, above all the ones avoiding insulation materials with high embodied carbon - such as the polymeric ones [10] [11] [12], possibly exploring the potential of bio-based products instead.

The trajectories outlined by these two guidelines - renewable materials and reversible building systems for structural purposes and bio-based products for the building envelope, should be further fine-tuned on the specific context. In fact, when examining the embodied energy and carbon of a construction product, a life-cycle approach encourages to evaluate its circular and decarbonisation potential in a wider framework. This assumption goes beyond climate parameters and the building systems' environmental performance, extending the scope to the geographical and economic features of the region by connecting two dimensions, the territorial sustainable management and the local supply chains, to examine their joint potential in improving the natural and built environments. Hence, to foster context-wise synergies maximising both circular patterns and carbon-neutral strategies, investigating bio-based products and renewable materials requires to adopt a multi-scale approach, building upon the local territorial features and socio-economic fabric.

With reference to the Italian North-East, its fragile territory presents inherent environmental risks - as the seismic and hydrogeological ones - more and more exacerbated by climate change. Several agricultural productions, consolidated in the area, could contribute to carbon sequestration, vulnerability reduction and soil regeneration, while offering, at the end of the growth cycle, a source for bio-based and renewable building materials in a short supply chain. Besides being a means to enact economic and ecologic sustainable processes that positively affect construction, this circular approach could also involve the local widespread and established network of SMEs with linkages to the building sector. In particular, furniture manufacturing, providing a solid know-how about wood-based panels and plywood, has to be considered.

Starting from these premises, the research "Integrated circular strategies and renewable materials", spanning 18 months, recently started within the context of the Interconnected Nord-Est Innovation Ecosystem (iNEST). Objective of the research is to examine bio-based products deriving from poplar and hemp, cultivations consistent with the Italian North-East agricultural production, to identify the potential synergies that could be activated between the territorial management, the architectural practice, and the local supply chains. This multi-scale and circular-based approach aims to link three dimensions:

- The application of poplar-based structural elements and of hemp-based insulation products in reversible building systems for existing and new constructions.

- The benefits produced by poplar and hemp plantations in terms of soil circular management and regeneration, carbon capture, and risk reduction.
- The supply chain perspective about the potential upscaling of the products and components deriving from these cultivations.

By examining and connecting these dimensions, the project adopts a synergic and context-based perspective of the circular management of material resources (Figure 1).

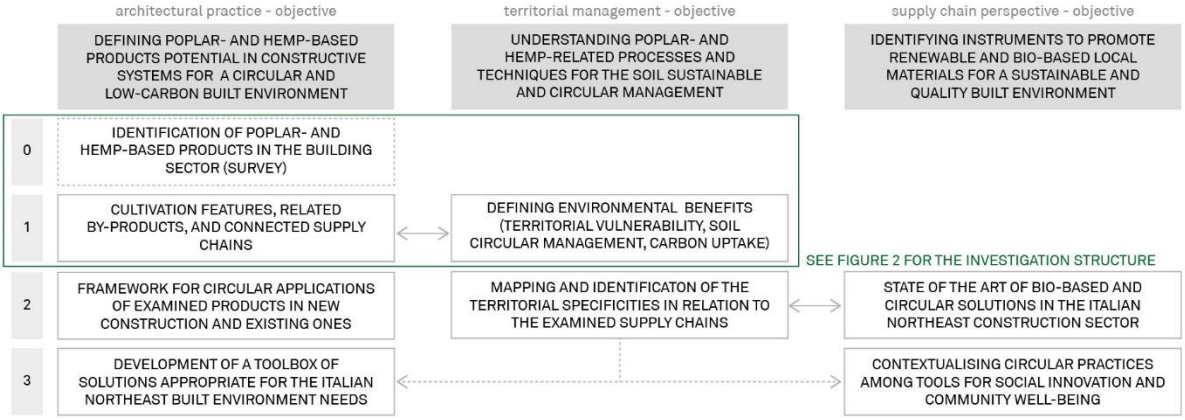

Figure 1. Workflow of the research

The contribution will describe how the state-of-the-art led to identify a range of products and solutions to be examined, paying attention to depict the different aspects supporting the upscale of these two biobased materials (Figure 2). Paragraph 2 will analyse the poplar and hemp agricultural productions in relation to the examined context, to identify their multiple outputs and several connected supply chains. Paragraph 3 will describe the benefits the two cultivations could produce on the territory, addressing soil remediation, risk reduction strategies, and carbon uptake. Paragraph 4 will contextualise poplar- and hemp-based products among current bio-based solutions in the building sector and will explore possible applications in new and existing constructions through circular constructive systems. Paragraph 5 will discuss the research following steps and identify the potential limitations, in light of the multi-scale circular-based approach and its objectives. Paragraph 6 will draw the conclusions.

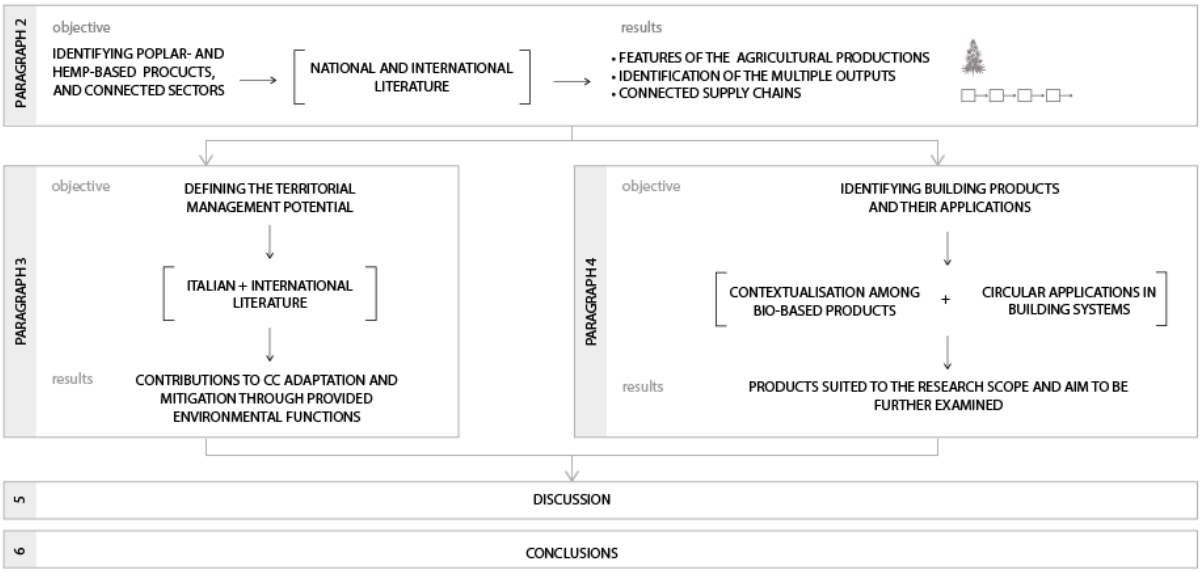

Figure 2. Structure of the paper

2. Poplar and hemp: from the agricultural production to the valuable outputs

The reason for steering the building sector attention towards poplar and hemp does not only rely on the environmental and cross-cutting benefits these plantations could provide, but also on their historical and future potential economic impacts examining the specific local context within the global economic scenarios.

When considering the construction transition towards an increase in the use of mass timber products, usually the benefits in terms of carbon storage are highlighted [13] [14], as well as the shorter timeframes for the structure assembly given its prefabricated and modular nature [15]. Nevertheless, two intertwined factors are sometimes overlooked: on the one hand, the actual climate benefits achieved by wooden constructions given the growth cycle of the trees used to source the materials and, on the other hand, the future availability of the wood resource itself [16]. In the European context, fir trees are the most common source for mass-timber structures as Cross-Laminated Timber (CLT) and Glulam. However, the increasing demand for this renewable resource could question its very renewable nature in a sustainable management perspective [17], ultimately endangering the fundamental role that forest could play in European climate change mitigation strategies [18]. Moreover, tree farming can be considered a means to meet the demand for construction products only if it provides the necessary materials within limited timeframes, and the importance bioeconomy is gaining as a driver could induce demand to exceed the total timber supply within few decades [6]. These circumstances highlight the importance of paying attention to the different trees' life cycle, focusing on the products derived from the fast-growing species - such as poplar.

When examining biobased insulation products and the related cultivations, different observations emerge. Besides being considered promising alternatives to construction carbon-intensive materials due to the generally low thermal conductivity [19], plants as hemp are put at the intersection of different supply chains and industries, among them: food and beverages, livestock nutrition, textiles, packaging, biomass, and biofuels. This implies considering, on the one hand, how each part of the plant can be used for producing different outputs and, on the other hand, that by-products and waste of each productive process could become a source for other industries through the adoption of circular and symbiotic patterns. Such perspective paves the way for building coordinated strategies in local and regional economies through the promotion of established and context-wise businesses, materials and crafts [20].

The depicted scenario stresses the importance of analysing poplar and hemp cultivations different aspects:

- The plants general features and the growth cycles usually adopted for the plantation and tree-farming activities.
- The different manufacturing processes taking place at the end of the growth cycle, and the related bio-based outputs derived from the various parts of the plant.
- The market products fabricated by using the identified outputs and the different economic sectors in which they are utilised.

In fact, as [16] underline, "appropriate biobased material choices consider the local supply chain and availability, sustainable cultivation, climate responsive architecture, and possibly add value to local agricultural practices by creating new streams for by-products' valorisation, as well as creating jobs in local communities". By outlining the current practices, processing and markets related to poplar and hemp cultivations, it will be possible to understand their role in the agricultural sector and related supply-chains. Following the construction of this framework, the potential in the territorial sustainable and circular management, as well as the use of the final products in the building sector and architectural applications will be examined.

2.1. Poplar tree farming: features, outputs and related sectors

In Northern Italy, tree farming has been a well-established industry since the early Twentieth century. Poplar cultivation, despite a decline in the last decades that led to a strong decrease in the dedicated area, represents an excellence in the wood-based production for industrial and energy use [21]. Although covering less than 1% of the whole forest territory, poplar provides almost half of the industrially

manufactured timber in the country [22]. Nevertheless, as institutional and private stakeholder recently underlined [23], its cultivation should be strongly enhanced to promote local manufacturing, as the national production currently only supplies about the 20% of the industrial wood-based products demand.

The most common clone used in poplar plantations is the so-called "I-214" (*P. ×canadensis*), characterized, on the one hand, by great adaptability to the climate and soil conditions, and, on the other hand, by intrinsic biologic features making it suited for the plywood and panels industries. Due to these features, and despite the clone's susceptibility to biotic threats [24], in decades its incidence on the total of poplar plantations gradually increased, almost leading to a monocultural model. In the last years, to foster biodiversity and a more sustainable model of territorial management, the MSA ("Maggiore Sostenibilità Ambientale" - hence, offering a greater environmental sustainability) clones have been introduced. These clones, proving a better resistance to the main biotic adversities, require less intense cultural practices and disease control interventions, also allowing for the same final processing adopted for I-214 clone.

The poplar cultivation generally relies on growth cycles between 8 and 10 years [21], sometimes up to 12 years. At the end of the cycle, three main processing of the tree can be carried out, depending on the part of the plant to be manufactured, on its technical features and on the desired final output [25]:

- Peeling is generally used for the lower part of the trunk, as it is possible to derive veneer layers useful for both the construction and furniture sectors final products.
- Sawing concerns a larger portion of the trunk and allows for many outputs that can be used in thicker final products.
- Chipping is used for the smaller branches up to the tree crown, and from this process particles and chips derive.

When choosing the correct processing for each part of the tree, the diameter and potential defects of the trunk are fundamental to consider for maximising the outputs. Figure 3 summarises the poplar farming growth cycle, connecting the further processing to the related outputs, these outputs' use in final products, and the related supply chains.

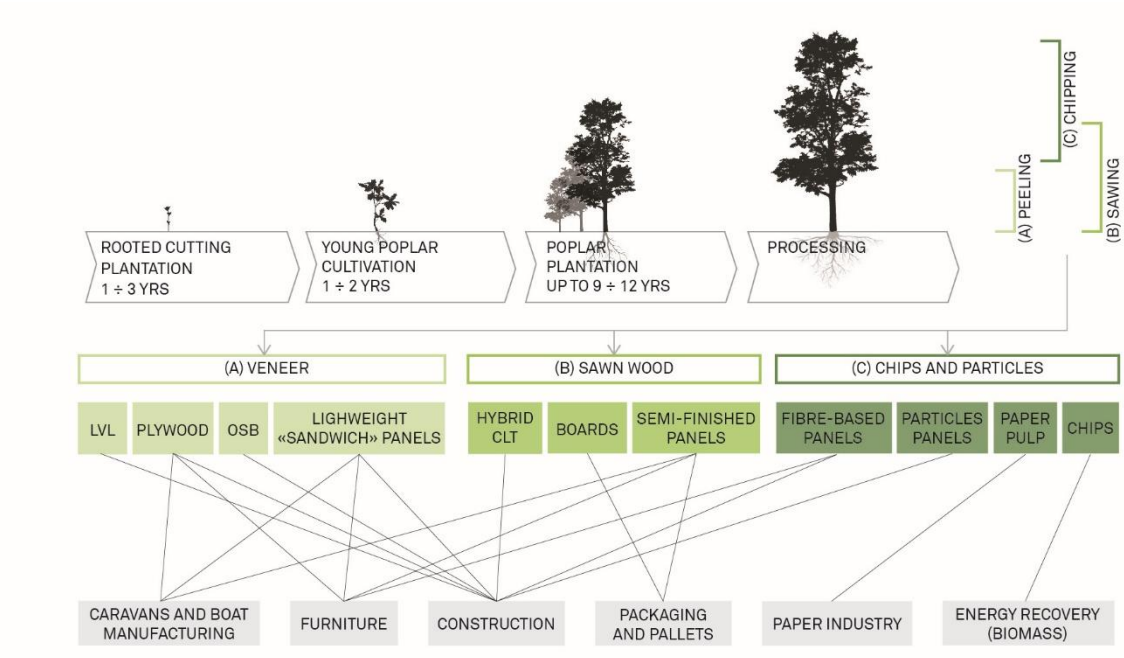

Figure 3. The poplar growth cycle, different outputs depending on the processing, their use in market products, and connected supply chains (adapted from [25])

More recently, polycyclic cultivations models were introduced. Based on management strategies that substitute cultivation inputs with natural dynamics, they are conceived to allow wood production by using different one or more main species (generally broadleaves trees), paired with accessory species [26]. These models, drawing from the historic agricultural tradition [21], aim to achieve growth synergies, a better conformation of the trunks, multifunctionality objectives, and the reduction of the risks deriving from monocultural models. By merging different productive cycles in a single plantation, not only biodiversity is differentiated, but also the quality and amount of wood-based products deriving from the final processing could increase if compared to a single clone farming model. This would ultimately guarantee a higher productivity of the plot just by making use of nature-based strategies. Three different cycles can be distinguished in a polycyclic model:

- very short rotation trees, mainly destined to biomass production, with a 1-2 years growth cycle.
- short rotation trees, used for veneer production, with a 10-12 years growth cycle.
- medium- to long- rotation trees, used for timber production, with growth cycles higher than 20 years.

In this model, poplar can fulfill different functions depending on the growth cycle it is positioned in: as a very short-rotation tree, it can be a source for biomass and wood-based panels, while, as a short-rotation tree, it is mainly used for veneer production through peeling operations [21] [27].

2.2. Hemp agricultural production: features, outputs, and related sectors

Hemp (*Cannabis sativa L.*) is one among the most ancient fibre-plants cultivated by man, mainly for textile and paper production, but also for medical and nutritional purpose. Despite being a consolidated production in the modern Italian economy throughout the whole territory, after World War II its production suddenly decreased, as more competitive textile fibres - at first natural ones, later synthetics ones, were introduced in the market. Due to the drop in the cost-effectiveness of hemp-related industrial activities, the interest in its cultivation decreased even though, in the previous decades, the country had been among the world leaders in its production, considering both the total extension of the area dedicated to plantations and the related throughput [28]. Moreover, the strict Italian normative about industrial hemp cultivation, originally conceived to contrast the opiates illicit crops and market, but almost irreversibly affecting the whole legal industry, prevented the Italian producers to resort to the European financing schemes that supported the other countries' industry in the early 1990s [29]. Recently, the political interests on this cultivation have been rising due to its potential significant value in many different economic sectors, and the agricultural production has been supported, especially in the Italian Northeast, through a more appropriate normative framework promoting the local production and supply chain [30] [31].

Hemp is an annual herbaceous crop currently distributed worldwide, with 120-150 days cropping cycle, that can supply a high yield of dry matter per ha [32]. Its intrinsic features, in particular the structure of the stem, make it possible to derive various different outputs by processing the several parts the plant is composed of, each one of them with specific technical characteristics to be taken advantage of, making hemp a multi-purpose crop. While the seeds, consumed raw or pressed into seed oil, are mainly used in the pharmaceutical sector and food industry, the outputs deriving from the stem processing represent an important resource for different markets. Analysed in a horizontal section, the stem structure can be divided in three different parts [32]:

- the hollow space at the centre.
- an inner layer, surrounding the empty core, composed by a woody material known as shives or hurds.
- an external layer, extending to the epidermis of the stem and containing the fibre bundles.

Depending on the processed component, the shives or the fibres, several outputs can be produced after the stem decortication. The shivs can be processed into animal bedding, construction materials, fiber board components, paper filler, or used as biomass; the fibres, depending on their length and quality, are used in the paper manufacturing, insulation products, carpets and cordages, or fibre boards [32] [33].

Figure 4 depicts the hemp plantation growth cycle, linking the different processing to the outputs, these outputs' use in various final products, and the many related supply chains.

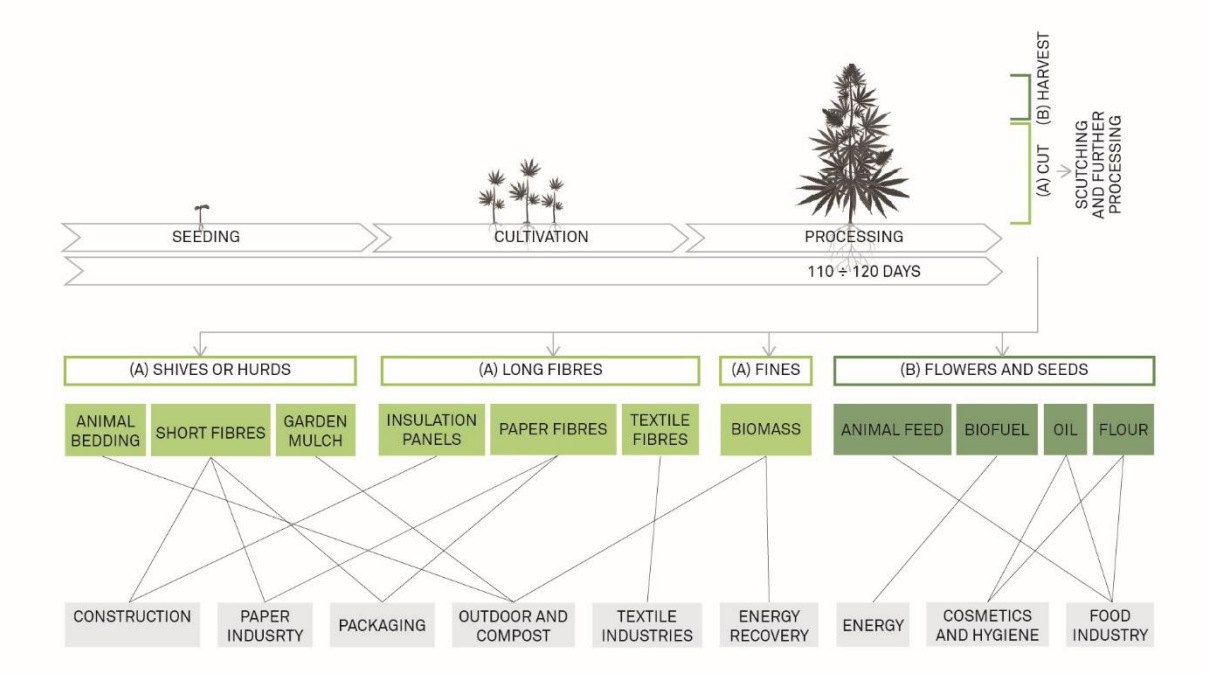

Figure 4. The hemp plantation growth cycle, the different outputs depending on the processing, their use in market products, and connected supply chains (adapted from [32] [33] [34])

3. Territorial benefits deriving from poplar and hemp cultivations

Poplar and hemp cultivation represent two agriculturally important resources in the sustainable management of the territory, with positive implications for the environment, economy, and society. These crops are particularly relevant for promoting circular and regenerative agricultural practices, actively contributing to carbon capture, climate change mitigation, and reduction of environmental risks [35].

One of the main benefits of these crops is their ability to contribute to the management of hydraulic risk. Poplar, with its deep and developed root system, has proven to be effective in hydrological regulation, absorbing and retaining excess water, reducing the risk of soil erosion and flooding [36] [37]. Similarly, hemp, with its abundant biomass and robust root system, can improve soil permeability, increasing its infiltration capacity and reducing the risk of floods [38].

Poplar and hemp crops also play a significant role in soil remediation. Poplar is known for its ability to absorb and accumulate contaminants, such as heavy metals, pesticides, and excess nutrients, contributing to the reclamation of contaminated soils [39] [40]. Hemp, on the other hand, has shown potential in decontaminating lands through the phytoremediation process, absorbing contaminants from the soil and accumulating them in its tissues [41]. In this sense, these crops are able to promote a sustainable and circular revitalization of the soil, through the contribution of organic matter and nutrients [42]. This is possible by cultivating them on degraded or unused lands, transforming them into productive areas and regenerating the soil. This circular approach promotes the valorization of the territory, favoring biodiversity, soil fertility, and ecological resilience [43].

For these reasons, the cultivation of poplar and hemp within agroforestry systems emerges as an innovative and multifunctional strategy for the sustainable management of the territory, combining tree or shrub forest crops with agricultural and livestock activities. This pioneering method, involving the trial of poplar and hemp crops, represents uncharted territory, offering a promising model for further

exploration. These systems are capable of providing a wide range of economic and environmental benefits, while presenting potential challenges related to decreased yields and homogeneity of technological characteristics [21].

Poplar stands out for its multiple environmental functions. It serves as a windbreak, contributing to the protection of surrounding crops from winds and harsh weather conditions, and constitutes an essential component of the ecological network. Its rapid growth and ability to absorb carbon dioxide actively contribute to carbon capture. This crop can also be used as a buffer strip to protect soils from erosion, particularly in the early years after planting when soil cultivation is limited. Poplar plantations have also been studied to reduce erosion in riverbanks during flood events, highlighting their potential in water regulation and soil protection [21], and playing a role in phytodepurating contaminated areas [21] [44]. Besides biomass production, SRF crops can provide a series of ecological services that have become more and more important over the last few years. Restoration of quarry sites or polluted lands, stabilization of riverbanks, and creation of ecological corridors are often accomplished with SRF cultivation. Recently, SRF plantations were used in research projects to evaluate the possibility of applying wastewater and sludge with different origins. While this is a quite new approach in Europe, there is an increasing interest in such systems for treating and reusing waste residues and simultaneously producing biomass for energy [44].

Despite the benefits, introducing poplar plantations on agricultural lands may result in transformations of lesser value compared to traditional practices of logging, such as obtaining materials for sawing, resulting in a reduction of economic value [21]. However, converting agricultural lands previously cultivated with cereals into poplar plantations can lead to a significant increase in the soil organic matter stock, compensating for potential reductions in the positive balance of carbon stored in the soil organic matter [21]. Concerning hemp, it can be considered a valuable crop when considering that, compared to other cultivations, it has a low fertilizer and irrigation demand; moreover, it can be used as well as in crop rotation practices before winter cereals, such as wheat [32].

In summary, the cultivation of poplar and hemp within agroforestry systems offers an integrated and sustainable approach to land management, promoting ecological resilience, climate change mitigation, and environmental protection. These systems represent an innovative solution that combines agricultural production, environmental conservation, and sustainable development [21] [44]. Table 1 synthetises the different ecosystem services that the two plantations provide.

Table 1. Ecosystem services provided by poplar and hemp cultivations [21] [45].

	Ecosystem service	Type
Poplar	production of industrial wood	supply
	water floods regime regulation and reduction of soil erosion	regulation
	reduction of the environmental impacts compared to the agricultural production	regulation
	filtering of the solutions circulating in the soil (nutrients and polluting substances)	regulation
	reduction of Greenhouse gases (GHGs)	regulation
	realisation of transition areas between the woods and the agricultural crops	regulation
	being an element of the ecological network	support
	conservation of the rural landscape	cultural and social
	biodiversity conservation	cultural and social
	public fruition for recreational purposes	cultural and social
Hemp	production of fibers for the textile industry	supply
	cultivation of seeds for human and animal consumption	supply support
	improvement of soil quality through erosion reduction	regulation
	groundwater filtration, removing excessive contaminants	regulation

	reduction of environmental impact compared to traditional crops	regulation
	minimization of greenhouse gas emissions	regulation
	creation of transition zones between forest and agricultural habitats	regulation
	increase of biodiversity through habitat creation for plant and animal species	support
	conservation and enhancement of the rural landscape	support
	integration into the ecological network to promote connectivity between different habitats	support
	promotion of cultural traditions related to hemp cultivation	cultural and social
	providing economic opportunities and employment for local communities.	cultural and social

4. Potential as circular and bio-based resources for the built environment

The brief analysis of the two agricultural productions in relation to the current market, together with the potential proved by poplar and hemp cultivations in the territorial and soil benefits, encourage research into the innovative application of their outputs in products for the building sector.

4.1. Hemp- and poplar-based products in the building market: an overview

Poplar solid wood is traditionally not considered suited to load-bearing applications due to the warping behaviour [46] that hinders its safe use, therefore boards represent the only building product derived from the tree's sawing. Nevertheless, as the construction practice is moving more and more towards the use of engineered wood, international research has been exploring how species less conventional than fir could substitute them in mass-timber or lumber elements. In fact, engineered wood can be organized in three main categories:

- Mass timber, including: Cross-Laminated Timber (CLT) - panels with isotopic performances used as load-bearing walls and slabs, and Glue-Laminated Timber (Glulam) - elements with a unidirectional behaviour and suited for one-way spanning applications as beams and pillars.
- Structural composites, including: Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL), Laminated Strand Lumber (LSL), and Oriented Strand Lumber (OSL), elements carachterised by a unidirectional orientation of the veneer or strands, hence suited for one-way spanning applications as beams and pillars.
- Panels, including: Plywood, Oriented Strand Boards (OSB), Medium Density Fibreboards (MDF), High Density Fibreboards (HDF), and particle boards. The structural or non-structural function of these products depends on their complying with the UNI EN 13986 [47] requirements.

As already mentioned, poplar is widely used for plywood veneer layers, both internal and external ones due to its aesthetic qualities; in these products, the layers can entirely derive from a single specie or be assembled according to a hybrid pattern. While these panels have been for decades a significant input as semi-finished products in the furniture components local industry [25], research is recently examining their wider potential in the building sector as load-bearing elements [48]. Also OSB panels can be produced by poplar strands, in a variable share up to the entirety of the wood used. Applications in mass timber are less common, at least in the Italian industry context, nevertheless several investigations assessed the suitable properties of CLT panels with poplar inner layers [49] [50]. Among the structural composites, LVL represents a recent field of investigation - also due to the growing demand of engineered wood products; although its use is more common in North American regions, demand in Europe is significantly expected to rise in the next yeas [51]. LVL can be composed of veneers belonging to different species, either coniferous or deciduous ones: among them poplar, proving good performances [52], although attention to the specific clone used must be paid [53].

Hemp is becoming quite popular in the eco-friendly construction field, although the latter is still a niche in the Italian market. Nevertheless, hemp-based products have been gradually spreading and, besides fibres or shives marketed as loose material, they can be organized in three main groups:

- Blocks, mainly composed of hemp shives with a small percentage of mineral component (lime), to be used for non-structural purposes. Thanks to the massive structure and the low conductivity of the material, they prove good thermal and acoustic properties, and are particularly suited to be used in the layering of the building's external walls, but also in the internal partitions. Their installation usually requires mortar.
- Panels, made up of compressed hemp fibres, to which a small percentage of natural bonding fibres or synthetic adhesives is sometimes added, used for insulation. These panels are suited to be applied the building envelope, hence both external walls and roof, but can used in horizontal and vertical partitions as well. The fiber structure of the panels guarantees significant acoustic performances, above all high noise absorption, and good thermal properties, depending of course on the specific density and compression rate of the fibres. Their installation is usually reversible.
- Pre-mixed products, including hemp shives, a binding agent - usually natural lime, and possible natural additives, to produce conglomerates for non-structural purposes. Among them, "hempcrete" (a mixture of lime and thick shives as fibre reinforcement in variable proportions) is used for the building envelope and inner partitions and can be both molded in place and sprayed. Lime plaster reinforced with thin shives is probably the hemp-based most known product and has been used as a finishing in internal and external partitions for decades.

All the hemp-based products ensure good hygrotermal performances, contributing to the indoor comfort in both new construction and renovation activities. Due to the carbon sequestered in the plant growth cycle, they can demonstrate an embodied carbon significantly lower than conventional alternative products [54]. Moreover, despite their natural origin, they are not subject to the activity of rodents, mites, and termites due to silica being present in the fibre. Nevertheless, as all bio-based insulation products, hemp insulating panels are affected by a lack of economic competitiveness when compared to synthetic materials [55] a factor affecting the users' penchant.

4.2. Circular applications in building systems: prospects and precautions

When exploring the possible upscale of poplar- and hemp- agricultural production in the research perimeter, attention must be paid to the features of the building products manufactured with the outputs deriving from these cultivations:

- they have to be suited for reversible building systems, to ensure the circularity prerequisite to be fulfilled.
- the possible uses in these systems have to be evaluated in relation to their potential weaknesses - as biobased materials, although performant and reliable, are not suited to all the functions that non-natural alternatives can take on.

Concerning the poplar-based products circular potential, all engineered wood elements can be installed with reversible fastenings, as they were conceived in the prefab building industry field. However, their durability and, consequently, their future proper management through reuse, depends on an installation that carefully avoids contact with water. Current building practice adopts a range of possible solutions protecting the engineered wood components from water absorption by detaching the elements from the ground through concrete or steel intermediate elements and paying attention to a correct waterproofing of the external walls and roofing systems. This concerns the most popular load-bearing elements (CLT and Glulam, with reference the Italian context), but the same rationale can be adopted for products that, although less common in the local architectural practice, can provide structural uses, such as panels. In particular, wood-based panels are subject to different environments depending on their position within the layering of a building system, a circumstance affecting their moisture content [56]. However, thermal modification can be a means to prevent the hygroscopic nature of wood elements to reduce their durability in time [57].

Examining hemp-based products in the multi-scale circular perspective of the research, all of them contribute to a productive synergy between the agricultural production and the building sector by valorising the shives. In fact, most of that output is treated as a low-value by-product of the crops in other sectors [58], while the thermal and acoustic performances it provides represent an important property in sustainable constructions. Nevertheless, considering the investigation scope, products not allowing reversible solutions - fibre reinforced conglomerates and plasters, fall out of it. As a consequence, only the application of panels and blocks in constructive systems will be examined in the next steps of the investigation, whereas they are produced and installed without mortar, or with a small and easily removable amount of adhesive substances. Concerning their specific use in the layering of a building systems, it has to be considered the significant hygroscopic features of hemp, resulting in an extremely high water absorption [12]. This especially affects the durability and performance of fibre-based insulation panels. Recent research [59] assessed how the contact with water produces relevant increases in both mass and volume of these elements, suggesting limiting the use of hemp fibre panels to controlled environments, "excluding any kind of contact with precipitation or any other source of water during storage and transportation, because full drying is impossible in natural conditions at a building site in case of water absorption". Nevertheless, the study also noticed how, if the layering of an external wall is properly designed, the panel should be protected except in case of damaged waterproofing.

5. Discussion:

The investigation outputs can be examined in two different perspectives: on the one hand, focusing on general remarks related to the literature analysis, and, on the other hand, in light of the cross-cutting and context-oriented approach on which the research is based.

Current national and international literature support poplar- and hemp-based construction materials and elements to be adopted for increasing the built environment sustainability. These observations rely on the multiple advantages provided by the two fast-growing agricultural productions, that encompass the territorial perspective and the building system scale. The renewable origin of these bio-based products and their feasible circular management through reversible constructive systems encourages research towards in-depth analysis of their potential through a life-cycle approach. However, the many ecosystem services and territorial functions provided by poplar and hemp also suggest how the adoption of a multi-scale perspective enhances the understanding of these cultivations' sustainable outcomes. Besides addressing carbon neutrality at different levels, this approach allows to jointly undertake several environmental challenges, as risk reduction and soil regeneration - ultimately building a synergic operational framework in the context of climate change prevention and adaptation. Nevertheless, it has to be noted that climate change itself represents a huge variable in the long-term effectiveness of the strategies relying on bio-based materials, despite their origin from fast-growing cultivations. In fact, the productivity and profitability of plantations could be challenged by restrictive irrigation associated with climate change, and significant variations in the rainfall regime could especially affect poplar Short Rotation Forestry (SRF) crops [44].

Contextualising the results in the research specific perimeter, two dimensions have to be considered: the local supply chains and industry, to build upon an existing know-how and potential, and the target in terms of building stock, identifying solutions suited to both renovation and new construction. Thus, by examining the investigation outputs, the most suited poplar- and hemp-based materials and elements should be identified as preliminary results on which basing the following steps of the study.

Given the local context manufacturing and economic fabric, poplar plywood represents a product on which the research should definitely focus on. This evaluation is supported, on the one hand, by the fast-growing and locally based nature of the resource that represents the necessary premise for a short supply chain, and, on the other hand, on the already existing network of SMEs providing the proper knowledge to explore poplar plywood potential novel applications. The latter would be suited to both new constructions and renovation or extension of existing buildings, either with structural purposes or in layering designed to improve the energy efficiency of the envelope.

With regard to hemp, panels and blocks are suited to multiple applications as well, all of them taking advantage of the thermal and acoustic properties provided by the material resource itself. However, although its agricultural production has been recently, and significantly, spreading in the North Italian area, the national producers' association reports a lack of processing plants in the Country for the fibres and shives manufacturing [29]. Given the recent political interest in supporting this cultivation as a local resource, the processing infrastructure will supposedly be established once the throughput value will be considered. This would create the missing link between producers and the several established companies in the territory involved in the eco-friendly construction products manufacturing and support a short supply chain in the sector.

Based on these observations, the following research next activities can be identified, to be carried out while defining the related normative framework:

- the involvement of the local supply chain actors, especially the ones active in the agricultural production and manufacturing, to examine barriers and enabling factors.
- the analysis of the geographical distribution of the existing cultivations, to cross-check territorial data and develop possible management strategies for risk reduction and soil regeneration.
- the exam of case studies proving a degree of innovation in the application of hemp-based panels and blocks and the analysis of poplar plywood structural applications, starting from the results of recent research conducted in Northwestern Italy - a geographical and climate similar context.

6. Conclusion

The contribution described the rationale and objectives of a multi-scale and circular-based research aiming to address carbon neutrality by connecting, through a context-wise approach, local fast-growing agricultural productions with three dimensions: the building sector, the territorial management, and the local supply chain.

The paper focused on the potential of poplar- and hemp- cultivations, defining the related growth cycles, outputs, final products, and related economic sectors. It then examined the multiple environmental functions provided by the two plants, such as carbon uptake, hydraulic risk reduction, soil protection and remediation, outlining their contribution to climate change mitigation and adaptation. Poplar- and hemp-based products were then contextualised among bio-based solutions in the building sector and were examined in light of three parameters: possible applications in reversible building systems, compatible functions depending on the material and technical features, and connection to the existing local manufacturing fabric. The results discussion steered the research next steps towards the study of innovative applications of poplar structural plywood and hemp-based panels and blocks, suited to both new constructions and existing buildings.

The investigation highlights how a multi-scale and circular-based approach allows to address carbon neutrality at different levels, beyond the construction component scale, possibly building a synergic operational framework in the context of climate change prevention and adaptation.

Author Contributions: Conceptualization, EZ; methodology, EZ and EF; investigation: EZ and EF; writing-original draft preparation: EZ and EF; writing-review and editing: EZ, EF, and EB; visualization: EB; supervision: EZ. All authors have read and agreed to the published version of the manuscript.

Acknowledgements

This research was funded by RFF NextGenEU, grant number ECS00000043, through the Italian National Recovery and Resilience Plan (PNRR), M4C2 - investment 1.5: Creation and strengthening of "Innovation Ecosystems for Sustainability", through the Interconnected Nord-Est Innovation Ecosystem (iNEST) research program - Spoke 4, CUP F43C22000200006.

References

[1] European Commission (2019). *Communication from the Commission to the European*

Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM (2019) 640 final.

[2] European Commission (2020). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A new Circular Economy Action Plan For a cleaner and more competitive Europe. COM (2020) 98 final*.

[3] Le Den X., Steinmann J., Kovacs A., Kockat J., Toth Z., Röck M., Allacker K. (2023). *Supporting a Roadmap for the Reduction of Whole Life Carbon in Buildings: Final report*. Luxembourg: Publications Office of the European Union. Doi: 10.2779/634412.

[4] United Nations Environment Programme (UNEP), Yale Center for Ecosystems + Architecture (2023). *Building Materials and the Climate: Constructing a New Future*. United Nations Environment Programme: Nairobi. https://wedocs.unep.org/20.500.11822/43293.

[5] Ministero delle Infrastrutture e dei Trasporti (2018), Decreto 17 gennaio 2018. Norme tecniche per le costruzioni. *G.U. S.G. 42, Supplemento ordinario n. 8*, 3-368.

[6] Pomponi F., Hart J., Arehart J. H., D'Amico B. (2020). Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits. *One Earth* 3 (2) 157-161. Doi: https://doi.org/10.1016/j.oneear.2020.07.018.

[7] Palladino D., Pagliaro F., Del Fatto V., Lavinia C., Margiotta F., Colasuonno L. (2019). *Stato dell'arte del patrimonio edilizio nazionale e analisi degli Attestati di Prestazione Energetica (APE). Report RdS/PTR2019/037*. Roma: Agenzia Nazionale per l'Efficienza Energetica (ENEA). https://www2.enea.it/it/Ricerca_sviluppo/documenti/ricerca-di-sistema-elettrico/ [accessed 24.04.2024].

[8] European Commission (2019). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. COM/2020/662 final*.

[9] ENEA (2023), *Rapporto anuale efficienza energetica: Analisi e risultati delle policy di efficienza energetica del nostro Paese*. Roma: Agenzia Nazionale per l'Efficienza Energetica (ENEA) https://www.efficienzaenergetica.enea.it/ [accessed 24.04.2024].

[10] Heeren N. and Hellweg S. (2018). Tracking Construction Material over Space and Time: Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows. *Journal of Industrial Ecology* 23(1), 253-267. Doi: https://doi.org/10.1111/jiec.12739.

[11] Streimikiene D., Skulskis V., Balezentis T., Agnusdei G.P. (2022). Uncertain multi-criteria sustainability assessment of green building insulation materials. *Energy and Buildings* 219, 110021. Doi: https://doi.org/10.1016/j.enbuild.2020.110021.

[12] Cosentino, L.; Fernandes, J.; Mateus, R. (2023) A Review of Natural Bio-Based Insulation Materials. *Energies* 16, 4676. Doi: https://doi.org/10.3390/en16124676.

[13] Oviedo D., and Keena N. (2022). Embodied Carbon: A call to the building industry. *IOP Conf. Ser.: Earth Environ. Sci.* 1122 012042. Doi: 10.1088/1755-1315/1122/1/012042.

[14] Verkerk P.J., Hassegawa M., Van Brusselen J., Cramm M., Chen X., Maximo Y. I., Koç M., Lovrić M. and Tegegne, Y. T. (2022). *The role of forest products in the global bioeconomy – Enabling substitution by wood-based products and contributing to the Sustainable Development Goals*. Rome, FAO. Doi: https://doi.org/10.4060/cb7274en.

[15] Pittau F., Malighetti L. E., Masera G., Lannaccone G. (2016). "A new modular preassembled timber panel for the energy retrofit of the housing stock". In: Eberhardsteiner J., Winter W., Fadai A., Pöll M. (Eds.), *Proceedings of the World Conference on Timber Engineering (WCTE 2016), Vienna, 22-25 August 2016*. Vienna: Wien University of Technology.

[16] Göswein V., Arehart J., Phan-huy C., Pomponi F., Habert G. (2022). Barriers and opportunities of fast-growing biobased material use in buildings. *Buildings and Cities*, 3(1), 745–755. Doi: https://doi.org/10.5334/bc.254.

[17] Raven P., Berry S., Cramer W., Creutzig F., Duffy P., Holtsmark B., Kammen D., Levin S., Lucht W. (2021). *Letter regarding use of forests for bioenergy. Letter to President Biden, President von der Leyen, President Michel, Prime Minister Suga, and President Moon (Policy Brief)*. Woodwell Climate Research Center. https://www.woodwellclimate.org/letter-regarding-use-of-forests-for-bioenergy/ [accessed 24.04.2024].

[18] Ceccherini G., Duveiller G., Grassi G., Lemoine G., Avitabile V., Pilli R., Cescatti A. (2020) Abrupt increase in harvested forest area over Europe after 2015. *Nature* 583, 72–77. Doi: https://doi.org/10.1038/s41586-020-2438-y.

[19] Carcassi O.B., De Angelis E, Iannaccone G, Malighetti L.E., Masera G., Pittau F. (2020). "Bio-Based Materials for the Italian Construction Industry: Buildings as Carbon Sponges". In: Della Torre S., Cattaneo S., Lenzi C., Zanelli A. (Eds.), *Regeneration of the Built Environment from a Circular Economy Perspective*, 237-247, SpringerOpen. Doi: https://doi.org/10.1007/978-3-030-33256-3.

[20] Dams B., Maskell D., Shea A., Allen S., Cascione V., Walker P. (2023). Upscaling bio-based construction: challenges and opportunities. *Building Research & Information*, 51(7), 764-782, Doi: 10.1080/09613218.2023.2204414.

[21] Corona P., Bergante S., Castro G., Chiarabaglio P.M., Coaloa D., Facciotto G., Gennaro M., Giorcelli A., Rosso L., Vietto L., Nervo G. (2018). *Linee di indirizzo per una pioppicoltura sostenibile*. Rete Rurale Nazionale, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Roma, ISBN: 9788899595968.

[22] Coaloa D., Chiarabaglio P.M., Giorcelli A., Pelleri F., Plutino M., Rosso L., Corona P. (2020). Profitability of poplar and hardwood broadleaves plantations in Italy. *Forest@ - Journal of Silviculture and Forest Ecology*, 17, 101-108. Doi: https://doi.org/10.3832/efor3595-017

[23] Regione Veneto (2015). *Allegato A alla Dgr n. 149 del 10 febbraio 2015. Intesa per lo sviluppo della filiera del pioppo*. Venezia, Italia.

[24] Corona P., Bergante S., Castro G., Chiarabaglio P.M., Coaloa D., Facciotto G., Gennaro M., Giorcelli A., Rosso L., Vietto L., Nervo G. (2023). *Italian hybrid poplar clones with greater environmental sustainability.* Rete Rurale Nazionale, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Roma, ISBN:9788833852683.

[25] Castro G., Fragnelli G., Zanuttini R. (2014). *La Pioppicoltura e il compensato di pioppo nell'inustria italiana*. Vignate: Lampi di stampa. ISBN: 9788848815802.

[26] Buresti Lattes E., Mori P., Pelleri F. (2017). *Cenni di progettazione e linee guida per il collaudo delle piantagioni policicliche*. Rete Rurale Nazionale, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Roma, ISBN: 9788899595500.

[27] Facciotto G., Minotta G., Paris P., Pelleri F. (2015). "Tree farming, agroforestry and the new green revolution. A necessary alliance". In: *Proceedings of the Second International Congress of Silviculture. Designing the future of the forestry sector. Florence, 26-29 November 2014. Firenze: Accademia Italiana di Scienze Forestali,* Vol. 2, 658-669. ISBN 978-88-87553-21-5. Doi: http://dx.doi.org/10.4129/2cis-gf-tre

[28] Bacci L., Baronti S., Angelini L. (2007). *Manuale di coltivazione e prima lavorazione della canapa da fibra*. Firenze: Istituto di Biometeorologia del CNR. ISBN: 9788895597034

[29] Federcanapa (2020). *Dossier canapa industriale: i nodi risolti delle politiche nazionali*. https://www.federcanapa.it/download/dossier-canapa-industriale/ [accessed 24.04.2024].

[30] Parlamento Italiano (2016). Legge 2 dicembre 2016, n. 242. Disposizioni per la promzion della coltivazione e dela filiera agroindustriale della canapa. *G.U. S.G.* 304, 30.12.2016, 5-8

[31] Regione Veneto (2019). Legge Regionale 08 agosto 2019, n. 36. Sostegno e promozione della coltivazione e della filiera agroindustriale ed agroalimentare della canapa (Canapa sativa L.). *Bur* 89.

[32] Ingrao, C., Lo Giudice A., Baceetti J., Tricase C., Dotelli G., Fiala M., Siracusa V., Mbohwa C., (2015). Energy and environmental assessment of industrial hemp for building applications: A review. *Renewable and Sustainable Energy Reviews*, Elsevier, 51(C), 29-42. Doi:

10.1016/j.rser.2015.06.002
[33] Carus M., Sarmento L. (2016), The European Hemp Industry: Cultivation, processing and applications for fibres, shivs, seeds and flowers. *European Industrial Hemp Association* 5, 1–9.
[34] Kaur, G. and Kander, R. (2023) The Sustainability of Industrial Hemp: A Literature Review of Its Economic, Environmental, and Social Sustainability. *Sustainability*, 15, 6457. Doi: https://doi.org/10.3390/su15086457.
[35] Ghale, B., Mitra, E., Sodhi, H.S. et al. (2022). Carbon Sequestration Potential of Agroforestry Systems and Its Potential in Climate Change Mitigation. *Water Air Soil Pollut* 233, 228. Doi: https://doi.org/10.1007/s11270-022-05689-4.
[36] Marapara, T. R., Jackson, B. M., Hartley, S., & Maxwell, D. (2021). Disentangling the factors that vary the impact of trees on flooding (a review). *Water and Environment Journal*, 35(2), 514-529.
[37] Christen, B., & Dalgaard, T. (2013). Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation. *Biomass and Bioenergy*, 55, 53-67.
[38] Amaducci, S., Colauzzi, M., Bellocchi, G., Cosentino, S.L., Pahkala, K., Stomph, T.J., Westerhuis, W.H., Zatta, A., & Venturi, G. (2012). Evaluation of a phenological model for strategic decisions for hemp (Cannabis Sativa L.) biomass production across European sites. *Industrial Crops and Products*, 37, 100-110.
[39] Oladoye, P. O., Olowe, O. M., & Asemoloye, M. D. (2022). Phytoremediation technology and food security impacts of heavy metal contaminated soils: A review of literature. *Chemosphere*, 288, 132555.
[40] Riccioli F., Guidi Nissim W., Masi M., Palm E., Mancuso S., Azzarello E. (2016), Modeling the Ecosystem Services Related to Phytoextraction: Carbon Sequestration Potential Using Willow and Poplar, *Appl. Sci.* 10, 8011; Doi: doi:10.3390/app10228011.
[41] Cleophas, F. N., Zahari, N. Z., Murugayah, P., Rahim, S. A., & Mohd Yatim, A. N. (2022). Phytoremediation: a novel approach of bast fiber plants (Hemp, Kenaf, Jute and Flax) for heavy metals decontamination in soil. *Toxics*, 11(1), 5.
[42] Breure, A. M., Lijzen, J. P. A., & Maring, L. (2018). Soil and land management in a circular economy. *Science of the Total Environment*, 624, 1125-1130.
[43] De Corato, U., Viola, E., Keswani, C., & Minkina, T. (2024). Impact of the sustainable agricultural practices for governing soil health from the perspective of a rising agri-based circular bioeconomy. *Applied Soil Ecology*, 194, 105199.
[44] Bergante S., Zenone T., Facciotto G. (2015). "Short Rotation Forestry for Energy Production in Italy: Environmental Aspects and New Perspectives of Use in Biofuel Industry". In: Bhardwaj, A.K., Zenone, T., Chen, J., (eds.), *Sustainable Biofuels. An Ecological Assessment of the Future Energy*. Berlin, Boston: De Gruyter, 137-153.
[45] Stevens, C. V. (2010). *Industrial applications of natural fibres: structure, properties and technical applications*. John Wiley & Sons.
[46] Maeglin R., (1985) Using Poplar Wood for Structural Lumber: The SDR Process, *22nd Annual Meeting of the Poplar Council of the United States*, 1985 June 25-27; Lawrence, KS.
[47] UNI (2015), UNI EN 13986:2015. Pannelli a base di legno per l'utilizzo nelle costruzioni - Caratteristiche, valutazione di conformità e marcatura.
[48] Alia-Martínez, M., Fernandez-Ceniceros, J., Antonanzas, J., Fraile-García, E., Urraca, R. (2015). "Innovative Modular Building Manufactured Using Structural Black Poplar Plywood Panels". In: Ayuso Muñoz, J., Yagüe Blanco, J., Capuz-Rizo, S. (Eds), *Project Management and Engineering. Lecture Notes in Management and Industrial Engineering*. Springer, Cham. Doi: https://doi.org/10.1007/978-3-319-12754-5_8.
[49] Das S., Gašparík M., Sethy A, Kytka T., Kamboj G., Rezaei F. (2023), Bonding performance of mixed species cross laminated timber from poplar (Populus nigra L.) and maple (Acer

platanoides L.) glued with melamine and PUR adhesive, *Journal of Building Engineering* 68, 106159. Doi: https://doi.org/10.1016/j.jobe.2023.106159.

[50] Hematabadi H., Madhoushi M., Khazaeian A., Ebrahimi G. (2021), Structural performance of hybrid Poplar-Beech cross-laminated-timber (CLT), *Journal of Building Engineering* 44, 102959, Doi: https://doi.org/10.1016/j.jobe.2021.102959.

[51] Verkerk, P.J., Hassegawa, M., Van Brusselen, J., Cramm, M., Chen, X., Maximo, Y. I., Koç, M., Lovrić, M. and Tegegne, Y. T. (2022). *The role of forest products in the global bioeconomy – Enabling substitution by wood-based products and contributing to the Sustainable Development Goals*. Rome, FAO. Doi: https://doi.org/10.4060/cb7274en.

[52] Liu Y., Gao Z., Ma H., Gong M., Wang H. (2021), Racking performance of Poplar Laminated Veneer Lumber Frames and Frame-shear Hybrid Walls, *BioResources* 16(1), 354-371, Doi: 10.15376/biores.16.1.354-371.

[53] Rahayu I., Denaud L., Marchal R., Darmawan W. (2015), Ten new poplar cultivars provide laminated veneer lumber for structural application, *Annals of Forest Science* 72, 705-715, Doi: 10.1007/s13595-014-0422-0.

[54] Rivas-Aybar, D.; John, M.; Biswas,W. (2023), Environmental Life Cycle Assessment of a Novel Hemp-Based Building Material. *Materials*, 16, 7208. https://doi.org/10.3390/ma16227208.

[55] Cardellini V. and Mijnendonckx J. (2022). *Synergies, energy efficiency and circularity in the renovation wave: Bio-based products for the renovation wave. ETC CM Report 2022/01, June 2022*. European Environment Agency (EEA) - European Topic Centre on Climate change mitigation. Doi: 10.5281/zenodo.6530825.

[56] Autengruber M., Lukacevic M., Grostlinger C., Eberhardsteiner J., Füssl J. (2021). Numerical assessment of wood moisture content-based assignments to service classes in EC5 and a prediction concept for moisture-induced stresses solely using relative humidity data. *Engineering Structures* 245, 112849. Doi: https://doi.org/10.1016/j.engstruct.2021.112849.

[57] Van Acker J.C.R., Jiang X., Van den Bulcke J.B.B. (2020). "Innovative Approaches to Increase Service Life of Poplar Lightweight Hardwood Construction Products". In: Serrat C., Casas J.R., Gibert V. (Eds), *Proceedings of the XV International Conference on Durability of Building Materials and Components (DBMC 2020), Barcelona, Catalonia, October 20-23, 2020*. Doi: 10.23967/dbmc.2020.086.

[58] Martinez B., Bernat-Maso E., Gil L. (2023). Applications and Properties of Hemp Stalk-Based Insulating Biomaterials for Buildings: Review. *Materials*, 16, 3245. Doi: https://doi.org/10.3390/ma16083245.

[59] Gaujena B., Agapovs V., Borodinecs A., Strelets K. (2020). Analysis of Thermal Parameters of Hemp Fiber Insulation, *Energies* 13, 6385. Doi:10.3390/en13236385.