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Review

# Basic Steps to Promote Biorefinery Value Chains in Forestry in Italy

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**Abstract:** Biorefineries are an important pillar to conduct the transition toward a circular bioeconomy. Forestry value chains produce wood biomass from harvesting and processing residues that have potential to be used in biorefineries, but currently, these residues are mostly used for energy generation. New biorefineries and new methodologies of wood fractionation allow the production of high value-added products based on carbohydrates and lignin. However, biorefineries based on lignocellulosic feedstock are still few in European countries and even less in Italy. The present study analyses the processes involved in a scenario of establishment of forest biorefineries, reviewing the main components and the actual organization of forestry value chains in Italy. The aim is to have a general vision, to identify and to focus the possibilities of the actual value chains and to fill gaps. The development of the territories is thought of in a perspective of a broader repertoire and more branched value chains than simple energy-generation end use, reviewing the tool for a feasibility study that could potentially involve lignocellulosic biorefineries also based on forest-wood industry feedstocks.

**Keywords:** multi-feedstock biorefinery; Trentino; biomass supply; ecological transition

## 1. Introduction

Over the past decades, the increase in the world population, the industrialization of developing countries, the over-exploitation of fossil fuels and progressive deforestation have triggered climate change, putting at risk the ecosystem's resilience. While the international community is pushing towards the development of a green economy, the new bio-based industries play an important role. Recently in Italy, the government has established a novel "Ministry of Ecological Transition", a strong political signal that shows the need to speed up a new development of society in compliance with the green deal principles set by the European Union (EU). In this new vision, forestry and forest-wood value chains can play different roles and strengthen their importance in the bioeconomy context. In Italy, wood manufacturing alone contributes 3.9% to the Gross Domestic Product (GDP), with 98,200 employers in 2020, and agriculture, forestry and fisheries are the first item of the bioeconomy-based balance (Italian Strategy of Bioeconomy). The recent pandemic triggered by COVID–19 showed that globalization represents a serious threat to the procurement of raw materials from foreign markets [1]. In the case of the timber industry, the concept of short supply in the forest-wood value chain as well as the diversification of activities and the establishment of new and more branched value chains can be considered as an element of resilience [2,3], especially in the economies of local territories. The principle of the circular economy is one additional pillar to the green economy that becomes even more relevant when applied to the wood industry. Considering the forest-wood value chains, the circular economy refers to the concept of "cascade use", which is too often referred to biomass for energy production, a sector that covers the largest part of wood residues recycling, not only in Italy but also in Europe [4,5]. However, in the context of the ecological transition, the bio-based industry, applied to the forestry sector, represents an innovation of the concept of cascade use due to its potential diversifications. It can support more articulated and more resilient supply chains, thus providing new job opportunities, especially in marginal areas. In this framework, the use of lignocellulosic biomass, as the most abundant renewable raw material available in nature, is also an object of interest for biorefineries because it can be utilized for the production of several valuable products such as bioethanol, bioproducts, power and heat production processes [6]. Recently, several scientific contributions have highlighted the potential of forest biorefineries, especially considering their advanced technological level, which places them close to being positioned in the market [7]. An example of the fast development of this sector is reported in the same study conducted by Stafford which reports that, until a few years ago, the synthesis of cellulose nanofibrils was considered still in the research phase. Nowadays, their development is already considered having reached TRL8 or close to entering the market as products of common use.

Despite the enhancement of environmental policies to encourage green initiatives and innovation through research projects, much still needs to be done, as demonstrated by a recent study conducted by the Joint Research Center (JRC) [8]. The study shows that the market of biobased chemicals, including man-made fibres, is around 3%. The JRC report highlights issues that still need to be clarified and gaps that must be filled between the different stages of the potential value chains, including especially those related to forestry.

Considering this context, the present article aims to identify the possibilities of developing new and more complex forest value chains in Italy from the point of view of the primary producer for biorefinery applications. Furthermore, the work highlights challenges and opportunities from a regional or macroregional supply chain development perspective and collects basic information needed for the progress and involvement of forest wood supply chains in biorefineries, with particular reference to data available for Trentino and generally for the Alpine area.

## 2. Forest Biorefineries Description

Figure 1 provides a map of the potential forest value chain that comprises both the traditional forest value chain (green highlighted) and a new and more branched chain consisting of biorefineries (yellow highlighted). It is worth noticing the opportunity to utilize part of the wood residues (yellow arrows) from forest operations and/or wood processing for biorefinery purposes or, alternatively, to use these wood residues for bioenergy production. In this way, the potentially added value recovered by the production of lignin, phenols and holocellulose can be enhanced. As reported in the flow chart (Figure 1), biorefineries still produce residues that can be utilized either for other industrial uses or energy generation. However, in Italy, almost all forest-based value chains end with energy generation, as reported in the green background of the flow-chart, because of the lack of biorefineries specialized in forest biomass recovery and a lack of logistic networks to allow potential forest biorefineries to be fed with wood residues.

In Europe, biorefineries based on lignocellulosic raw materials are mainly linked to biofuels or pulp and paper production. They are generally referred to as "second-generation" refineries (2G) [9], including biorefineries fed with agricultural residues (e.g., straw, sugar cane bagasse), municipal waste and waste from wood processing.

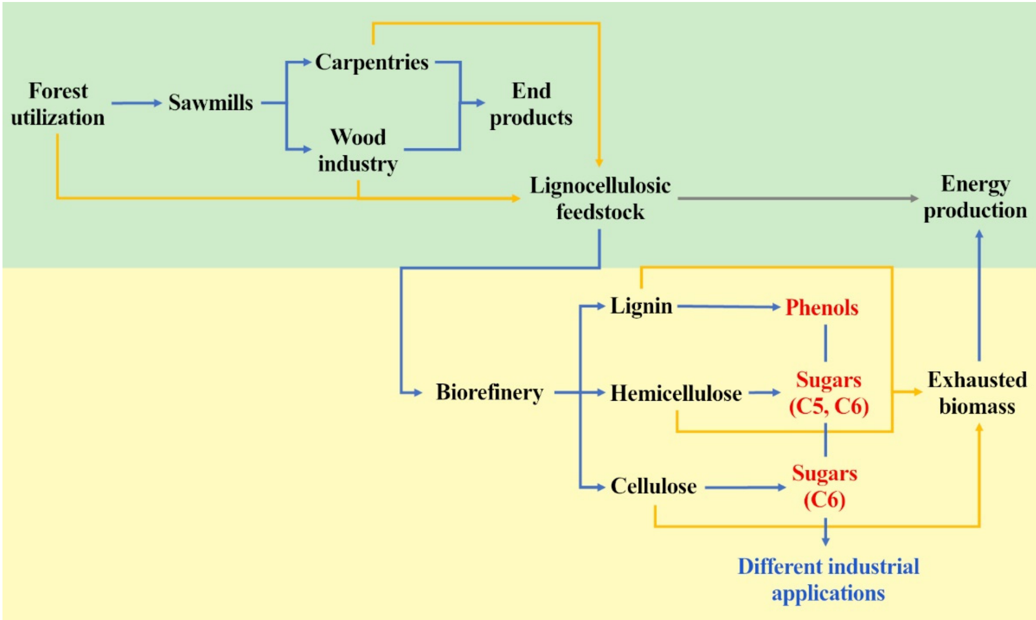


**Figure 1.** Organization design of the forest-biorefinery value chain, with particular attention to its residues. Traditional forest value chain is highlighted in green and the biorefinery branch is in yellow. Arrows in blue represent the flow of commercialized product, yellow arrows represent residues flows.

The fragmentation of lignocellulosic biomass into its main components, holocellulose (polymeric chains with monomers containing five or six carbon atoms) and lignin, allows different and innovative uses. Cellulose is a polymeric chain of glucose, a six-carbon sugar (C6 sugar), while hemicellulose is a polymer of mainly five-carbon sugars (C5 sugars). Carbohydrates could provide building blocks for fibres such as nanocelluloses and many other chemical intermediates [7]. Recently, interest in lignin has significantly increased, providing new opportunities in different sectors. Initially considered a waste from the pulp and paper industry, lignin is conquering new markets [10]. The potentialities of lignin, at different steps, was described by Liu, et al. [11] as follows: (1) biopolymer component in thermoplastic polymer blends; (2) improvements in the interfacial properties of lignin by chemical modification and or grafting provide better compatibility with synthetic polymers; and (3) lignin can be depolymerized into monomers in order to be converted into platform chemicals for the synthesis of several polymers. Lignin from 2G biorefineries and pulp mills can be chemically and biochemically used to produce essential green value-added phenolics, i.e., vanillin, PHA, BTX, phenolic aldehydes, composites, high-performance lignin-based carbon fibres, adhesives, graphene battery electrodes for energy storage, resins, fillers, pigments, additives in the cement industry, adsorbents and dye preparations as an alternative to petroleum-based chemicals [12–14]. Furthermore, the new opportunities offered by the transformation of lignin at the nano-scale are very promising [14,15].

In the pulp and paper industry, both lignosulfonates (deriving from sulphite pulping) and kraft lignin cover most of the current market, and the sulfite pulping process accounts for 1 Mt/year of lignin-based commercial products. The market for lignosulfonates is continuously increasing, and they need proper treatments to be used for specific purposes for example for food (i.e., vanillin). Instead, the commercialization of Kraft lignin in a reasonably large scale is just starting, and its end use is shifting from an exclusive burning product in pulp mills towards an added value for chemicals [16]. Because of the high potentialities of the lignin compounds, in the recent years, pilot plants for the Lignoboost or Lignoforce process have been built and addressed to exploit lignin extracted and purified by precipitation from Kraft black liquor as much as possible. Lignoboost produced about 8000 t/year in its pilot plant in Sweden in 2007, but today, the production of Kraft lignin is at industrial scale, with an impressive annual capacity of 50,000 Mt/year by several LignoBoost plants in Finland in 2015 [13].

Another process suitable for biorefineries that allows the separation of lignin from cellulose and that can be operated at pre-industrial or industrial level is the organosolv process, a system that has not yet fully reached the market. However, the organosolv shows a series of interesting characteristics such as high yields (Table 1) and the possibility of obtaining lignin with low structural modifications relative to the native lignin in the used feedstock. Consequently, this allows making products with customizable specifications, exploiting the original characters of the feedstock. Nevertheless, the organosolv method can produce intractable polymers, characterized by condensed units, not suitable for further depolymerization processes [17].

A full exploitation of the potentialities in forest biorefineries cannot neglect elements that affect the quality of the final product such as the wood species and the extraction process used. For example, Kraft lignin, used as precursor in the manufacture of porous carbon nanofibres for supercapacitors, gave different results when using conifers such as pine instead of broadleaved trees such as eucalyptus [18]. The lignin extraction process is also important as it affects the reactivity of lignin. Indeed, most of the extraction methods try to reach at the end a rather high lignin reactivity, which is indicated by a low degree of condensation, low molecular weight, high amounts of β–O–4 linkages and low amounts of carbohydrates impurities [16].

Recently, a new generation of multi-feedstock biorefineries entered the market processing from 500 t (pilot scale) up to 20 kt (industrial scale) of biomass annually. Their patented process is partially known and starts with a pretreatment of the feedstock using phosphoric acid [19] and applying mild conditions regarding temperature and pressure. Due to the greater versatility and the reduced amount of feedstock required by this biorefinery type, newly organized value chains could be adapted to forest territories with limited forest volumes. A multi-feedstock biorefinery responds to a modern concept of lignin-first processes, which [17] were described according to the following main steps. First, lignin is removed from whole biomass using an organic solvent or acids as catalysts. Then, the resulting intermediates are stabilized to avoid condensation reactions and finally further depolymerization reactions happen if the depolymerization was not complete at the stabilization stage. In this approach, the purpose is to evaluate the final product lignin and cellulose for new high-value applications.

A multi-feedstock biorefinery, due to the small amount of initial feedstock required, makes the procurement process less complex. It also allows changing the type of incoming biomass, with shorter time intervals, considering the initial different chemical structure of the matrix (conifers, broadleaved trees and different wood species). In this context, the biorefinery is able to absorb any impacts on production due to sudden interruptions in the supply chain that may occur due to extreme and unpredictable climatic conditions, such as windstorms.

There is not much data available regarding the yields of biorefinery plants. However, Table 1 reports indicative values related to the processes and products considered interesting and potentially useful for the development of a biorefinery based on a forest biomass, including the classic processes for pulp production.

Moreover, different extraction methods affect the yields of the chemical compounds of a certain biomass. The pretreatment can increase the yield and change the ratios of the chemical composition. Tian, et al. [27] decided to use a two-stage pretreatment to extract lignin from poplar wood chips in order to increase hemicellulose recovery. Common single-stage delignification pretreatments (such as organosolv or alkali) are effective for lignin extraction, but on the other hand, the severe conditions to solubilize lignin usually end up in a high loss of hemicellulose [25,27].

**Table 1.** Indicative values related to biorefinery processes and related products.

| Species | Treatment | Yield | Source |
|---|---|---|---|
| Poplar by short-rotation coppice (SRC) and mischantus | Organic solvents followed by enzymatic saccharification for microbial conversion | 70% glucose | [20] |
| Conifers, hardwoods | Kraft lignin. Softwood 170 °C, 4.5 h, alkali 25%, sulphidity 25% alkali 25%; hardwood 165 °C, 4.5 h, active alkali 22%, sulphidity 20% | 50% phenolics | [21] |
| Birch sawdust | Ru/c treatment | >90% solubilization, yielding 52% phenolic monomers | [13] |
| Softwood | Organosolv | 85% of the original lignin, 67% of the original cellulose | [22] |
| | | 0.5 kg of lignin per kg ethanol | [23] |
| Pine | Delignification process by sulphate method | Pulp yield 36.9 to 47.2% | [24] |
| Mixed wood (spruce, pine, Douglas fir) | Organosolv | 89.7% of glucan—90% bioethanol yield (8 h of process) | [25] |
| Conifer | Chemical pulp | 42–50% | [26] |

## 3. Forest-Wood Chain Feedstock

### 3.1. General Concepts

The involvement of biorefineries in forestry value chains in Italy cannot ignore the actual administrative organization in regions and the characteristics of the different types of collected biomass. If considering a forest value chain in support of biorefineries, we need to take into consideration three main steps: (1) forest residues from harvesting, (2) sawmilling (first wood processing) and (3) the wood industry and carpenters (Figure 1). Currently, in Italy and in the Alpine region, the most common end use of wood residues is the direct production of energy in district heating plants (DHPs) and combined heat and power plants (CHPs) [4,5], except for minor amounts of forestry biomass intended for mulching and the production of panels.

Wood feedstock is considered less consistent in its composition compared to the dedicated perennial crops, so the latter is more suitable for conversion with specific quality requirements [20]. Indeed, Forest Lignocellulosic Biomass (FLB) could find use in biorefinery when it is a residue from thinning or logging operations containing also branches, tops, bark and sometimes even stumps. Comparing biomass coming from forest and biomass from first processing industry, it is evident that the first has a high moisture content (even more than 100% referred to the dry weight). The moisture content depends on different factors such as the season of cutting or the presence of reaction and juvenile wood complicating the biorefineries supply situation even more. Furthermore, forest biomass is characterized by a high content of impurities (i.e., leaves and needles) which cannot easily be separated from the initial biomass [17]. In tree plantations, cultivation practices (watering practices, fertilizers, herbicides, etc.) affect the final chemical wood composition [17]. All these factors together significantly affect the biomass transformation process.

The moisture content of the feedstock can impact on the value chain organization and the efficiency of the process. New generation biorefinery plants can run with 80% of dry matter, but it is also feasible to run the process with 60% of dry matter. The hydric content requested by the plants is usually about 30–40% (about 66.6–45% referred to the dry weight).

Feedstock coming from first processing industries, such as sawmills, produce a number of residues such as sawdust, woodchips and shavings with lower humidity content and usually debarked material. Thus, it can be an ideal feedstock for biorefinery development.

Another major concern is the use of residues from the wood industry which are contaminated by additives such adhesives and coatings. In many cases, this type of wood residues can only be used for the production of particleboards. Otherwise, they have to be considered for disposal and are not suitable at the state of the art for biorefinery development (e.g., the residues from the XLAM industries).

In the new concept of biorefinery, the planning of the "sourcing and preparing" stage of the feedstock is essential. However, this requires knowing the variability of the incoming biomass and usually extractives, and ash must be removed because some components can interact with applied catalysts [17].

In forest value chains dedicated to biorefineries, it is crucial to establish a plan for assessing the sustainability of the supply chain. Thus, it is important to quantify the available biomass, the related potential availability of lignin and cellulose and calculate the potential extraction of other compounds. In this regard, it is worth mentioning that an ideal biorefinery could first extract the targeted compounds and subsequently isolate lignin and cellulose. In the extraction processes adopted by biorefineries, some processes, such as the auto-hydrolysis process for the recovery of antioxidants and cellulose, have provided interesting results, although much remains to be done to reduce the risk of damaging the remaining molecules [28].

### *3.2. Chemical Composition and Specific Applications*

In the perspective of a forest biorefinery, it is also important to take into consideration the quality of the incoming biomass resource, i.e., poplar lignin appears to have a broader application of low-molecular lignin due to its higher number of more reactive and sterically unhindered aliphatic groups [20].

It is commonly acknowledged that the main components of wood are lignin, cellulose and hemicellulose, in addition to smaller amounts of other extractives and ashes (Figure 2) [29,30].

The amount of a certain substance in a woody biomass depends on the origin and history of that biomass; the main factors are tree anatomy, age, geographical origin extraction method and aging.

Bark can be considered a specific feedstock in the biorefinery concept. Bark tissue has a chemical composition different from wood regarding the contents of lignin and cellulose that depend on the age of the tree. Furthermore, the chemical structure of lignin and cellulose is quite different as it was shown for some species such as eucalypt [31]. Bark can be considered an additional resource that can produce furanic compounds such as 5-hydroxymethylfurfural (HMF), furfural (FF) and derivatives such as levulinic acid (LA) in a modulated biorefinery concept [31]. The bark of Pequi (*Caryocar brasiliense* Cambess) allows for such high yields that it can be considered a standalone element in a biorefinery [32]. In applications of bulk bark, bark components were successfully utilized in producing bark-based epoxy resins, polyurethane foams and phenol formaldehyde adhesives. Furthermore, bark is sometimes rich in tannins, which have very powerful biochemical activities (antifungal, antioxidant activity, as well as anticancer and antidiabetic activity). In addition, tannic acid (TA) contained in bark was used as a gelation binder to crosslink polyvinyl alcohol (PVA) and obtain new hydrogels.

Comparing wood and bark, the extractives content is very high in bark, as it can sum up to 60–80% of the biomass dry weight [33].

Forestry timber is usually debarked, while branches are not debarked. Indeed, their chemical composition is always reported as a mixture of wood and bark, so the ratio between them is determined by branch size [33]. For example, oak bark is usually 10–20% of the log volume, while it is 20–35% of the branches [34]. This fact, namely, branches with bark vs. debarked stems, explains why the extractive amount is higher than in the stem for branches of the same weight.

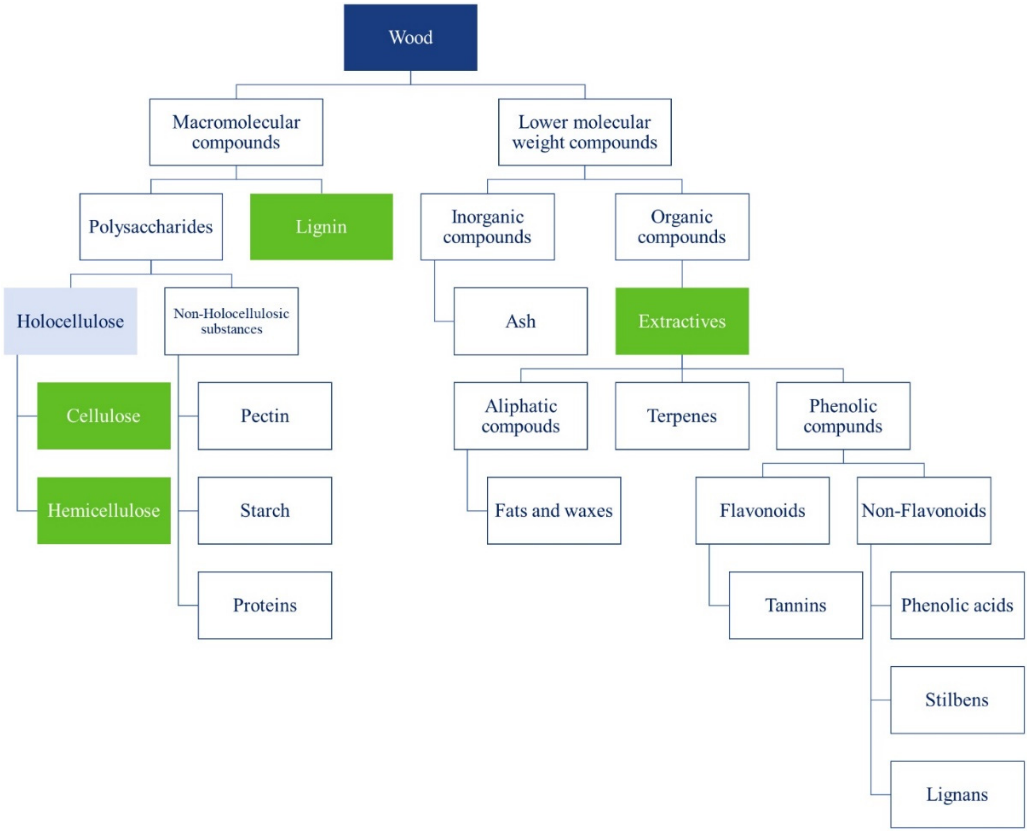


**Figure 2.** Classification of the main components contained in wood.

Wood chemical composition is also affected by the presence of reaction wood, which is always present in branches of both conifers and broadleaves, so the presence of branches in the original feedstock strongly affects the quality and quantity of the main components (cellulose and lignin). In tree species where a differentiated heartwood is present, the chemical composition must take into consideration the amount of extractives in the heartwood. It was shown that juvenile wood has less cellulose and ash and more hemicelluloses, pentosans and lignin compared to mature wood. There is a gradual increase in cellulose content as the cells mature and a gradual decrease in hemicellulose content, whereas lignin decreases more rapidly with cell maturity [29,35]. Taking into account the forest biorefinery concept, a wood supply from thinning operations can affect the quality of lignin and cellulose after their disruption compared to an adult tree.

Geographical origin also affects chemical properties: not only are the ratios different between the various places but also the type of extractives are not the same [36]. Prida and Puech [36] analysed extractives of oak wood from America, France and Eastern Europe (Moldova, Ukraine and Romania), and they state that whiskey lactone and ellagitannins levels can be used as discriminant to understand the origin of the biomass. Even lignin composition differs according to the origin [37].

In Table 2, an idea of the possible resources to be found in different wood species are listed, looking to the species spread in the alpine area.

**Table 2.** Percentage of dry weight for the different compounds present in wood material and references. * [a] Arabinogalactan; Holocellulose (HoC), [b] Klason lignin (KL); Pentosans (PNT); [c] α-cellulose; [d] Seifert's cellulose; [e] Kürschner–Hoffer cellulose; [f] Ethanol extracts.

| | Tree Part | Hemi-Cellulose | Cellulose | Lignin | Extractives | Ash | Comments * | Source |
|---|---|---|---|---|---|---|---|---|
| *Larix decidua* | Wood | | | 26 | | 0.2 | | [29] |
| | Wood | 5–35 [a] | | | | | | [38] |
| | Bark | | | | 3.8–6.7 | | | [38] |
| | Heartwood | | | 31.4 [b] | 9.4 | | HoC 60%<br>KL 31% | [39] |
| *Picea abies* | Wood | 24.3 | 41 | 30 | | | | [40] |
| | Wood | 21.2 | 50.8 | 27.5 | | 0.5 | | [41] |
| | Wood | 20 | 45.6 | 28.2 | 5.9 | 0.3 | | [42] |
| | Wood | 29.4 | 43 | 27.6 | 1.7 | 0.6 | | [30] |
| | Wood and Bark | 27 | 42 | 26 | | | | [43] |
| | Bark | 28 | 22 | 31 | 15 | | | [44] |
| | Stem wood | 27.3 ± 1.6 | 42.0 ± 1.2 | 27.4 ± 0.7 | 2.0 ± 0.6 | | | [33] |
| | Bark | 9.2 ± 1.1 | 26.6 ± 1.3 | 11.8 ± 0.9 | 32.1 ± 3.8 | | | [33] |
| | Branches | 30 | 29 | 22.8 ± 1.7 | 16.4 ± 2.6 | | | [33] |
| | Needles | 25.4 | 28.2 | 8.4 ± 2.1 | 43.3 ± 2.3 | | | [33] |
| | Stump | 27.9 | 42.9 | 29.4 ± 1.8 | 3.8 ± 0.2 | | | [33] |
| | Roots | 19.2 | 29.5 | 25.5 | 15.7 | | | [33] |
| *Pinus sylvestris* | Wood | 28.5 | 40 | 27.7 | 3.5 | | | [45] |
| | Wood | 20.3 | 46.9 | 27.3 | 5.1 | 0.3 | | [30] |
| | Bark | | 47.0 [c] | 28.0<br>27 | | 0.2<br>0.4 | PNT 11% | [29] |
| | Bark | | 32.5 [c] | 27.28 | 18.33 | 2.4 | | [46] |
| | Bark | | | 49.2 | 9.34 | | HoC 43.7% | [46] |
| | Bark | | | 32.9 | 18.8 | 4.6 | HoC 36.6% | [47] |
| | Bark | 25 | 19 | 38 | 18 | | | [48] |
| | Bark | 25 | 19 | 38 | 11 | | | [44] |
| | Bark | 8.1 ± 0.4 | 22.2 ± 3.2 | 13.1 ± 5.4 | 25.2 ± 5.2 | | | [33] |
| | Stem wood | 29.6 ± 0.6 | 40.7 ± 0.7 | 27. ± 0.0 | 5.0 ± 1.0 | | | [33] |
| | Branches | 32 | 32 | 21.5 ± 5.9 | 16.6 ± 7.1 | | | [33] |
| | Needles | 24.9 | 29.1 | 6.9 ± 0.8 | 39.6 ± 1.3 | | | [33] |
| | Stump | 28.2 | 36.4 | 19.5 | 18.7 | | | [33] |
| | Roots | 18.9 | 28.6 | 29.8 | 13.3 | | | [33] |
| *Populus* spp. | Wood<br>*P. alba* | | 52.0 [c] | 16.0 | | | PNT 23% | [29] |
| | Wood<br>*P. alba* | 23 | 52 | 16 | | | | [48] |
| | Wood | 24 | 49 | 20 | 5.9 | 1 | | [30] |
| | Bark<br>*P. alba* | | 35.58 | 28.17 | 19.43 | 1.6 | HoC 54.93% | [46] |

**Table 2.** *Cont.*

| | Tree Part | Hemi-Cellulose | Cellulose | Lignin | Extractives | Ash | Comments * | Source |
|---|---|---|---|---|---|---|---|---|
| | Bark *P. nigra* | | | 33 | 13 | 5.8 | | [49] |
| *Fagus sylvatica* | Wood | | | 19.8 | 1.8 | | | [50] |
| | Wood | 22.3 | 41.6 | 25.9 | | | | [51] |
| | Wood | | | | | | | [52] |
| | Wood | 31.8 | 45.8 | 21.9 | 0.4 | | | [41] |
| | Wood | 33 | 42 | 20 | 2 | 0.2 | | [30] |
| | Wood | 33.5 | 44.2 | 21.8 | 2.6 | 0.5 | | [30] |
| | Wood *F. orientalis* | | $43.9 \pm 0.03$ [c] | $23.6 \pm 1.83$ | | | HoC $73 \pm 0.19\%$ | [53] |
| | Bark *F. orientalis* | | 32.3 | 24.63 | 15.5 | 1.95 | HoC 50.07% | [46] |
| | Bark *F. orientalis* | | | 32.87 | 5.5 | | HoC 63.52% | [46] |
| | Bark | | | | 1.8–2.4 | | | [38] |
| *Quercus* spp. | Wood | | 39.82 [b] | 24.52 | | 0.17 | [b] Seifert's cellulose | [54] |
| | Wood | $24.48 \pm 0.24$ | $39.70 \pm 0.98$ [d] $41.78 \pm 0.26$ [e] | $27.43 \pm 0.6$ | $8.14 \pm 0.85$ [f] | $0.23 \pm 0.04$ | HoC $64.19 \pm 0.74\%$ | [55] |
| | Bark | | | 30.82 | | 13.5 | HoC 50.59% | [46] |
| | Bark | | 33.57 | 33.57 | 11.4 | 10.2 | HoC 44.79% | [56] |
| | Bark | 12.0–16.1 | 23–24 | 19.5–32.7 | | $8 \pm 2$ | | [34] |
| | Bark | 9.3 | | | | | HoC 53% | [29] |
| | Bark | | 20.79 | 32.67 | 18.75 | 1.73 | HoC 45.91% | [46] |

A full exploitation according to a biorefinery concept of forest feedstock might consider the following points:

Heartwood and knotwood extractive compositions are very species-specific. For example, Larch heartwood and knotwood show a high amount of polysaccharides, most likely arabinogalactans. Scots pine heartwood and knotwood are rich in both fatty and resin acids and poor in phenolics. Oak heartwood is instead rich in phenolic monomers and condensed tannins (CT) but contains only traces of non-polar compounds [57].

Hardwood knots contain more hydrophilic and polar extractives, while softwood ones contain extractives that are more lipophilic and of lower polarity [58].

Knotwood contains higher quantities of extractives than heartwood, the lower concentrations of knot extractives are in hardwoods while the highest concentrations were in softwood [59], with some exceptions, such as oak [58].

Sapwood's extractives contents are low, thus, sapwood is a poor source of any kind of extractive [57].

Barks are very rich in all types of extractives, especially in CT and polysaccharides. Scots pine and Norway spruce particularly appear to be good sources for these two extractives classes [57].

The analysis of twigs highlighted Scots pine and Norway spruce as potential sources for non-polar extractives and, in particular, terpenes, which are combined with a larger fraction of saccharides than in heartwood or knotwood [57].

Needle extractives are mostly constituted of phenolic monomers and monosaccharides, composed, therefore, of mostly small molecules [57].

Lignans were confirmed to be present in all softwood species studied while they were totally lacking in hardwoods, which contain flavonoids and saccharides. Even if the role of lignans in lignin formation is still under discussion, an explanation of the presence of lignans in softwoods might be their involvement in the lignification of compression wood. Compression wood is reported to contain higher amounts of lignin than normal wood. The fact that tension wood is reported to contain higher amounts of polysaccharides could be in accordance with the high amount of saccharides detected in hardwood knots. However, these hypotheses are purely speculative [58].

### *3.3. Supply of the Feedstock and Organization of the Value Chain*

#### 3.3.1. Feedstock Amount

FLB is acknowledged as the most available feedstock for non-food production [59], and it was estimated that 232 million tonnes of wood was supplied by the EU 27 in 2011 [20]. Nevertheless, there are still relevant issues to take into consideration in planning a FLB production chain. It is important to know the availability of raw material supply for a potential biorefinery on a regional scale and then evaluate the potential availability of forest and industrial wood residues. The FLB estimation is becoming an increasingly important parameter for consideration in the organization of transports since the new biorefineries offer the possibility of processing different woody tissues that have different volumes and weights, therefore capable of influencing the load capacity of each single transport. Due to the difficulty of collecting data on the quantities of forest and sawmill residues, in Italy, detailed estimates of FLB are not yet available at a national level. In addition to the data collection problems, there are also observations of a methodological nature as they tend to underestimate the quantities of biomass. The underestimation of the uses was confirmed both by satellite analyses and by the National Forest Inventory of 2005. These comparisons show that the availability of biomass is often greater than the estimates reported, even up to 40% higher [60]. Verkerk, et al. [61], in the assessment of biomass in Europe, estimated that the potential biomass available in Italy is mainly found in northern regions, with a high potential in Alpine areas.

Starting from the evaluation conducted by Verkerk, et al. [61], the availability of FLBs from the two main forestry production chains, forestry enterprises and sawmills, was estimated in the Trentino Alto Adige, Tuscany, Liguria and Piedmont by a literature review. The first document taken into consideration was the Italian National Forest Inventory (INFN) which, in the last assessment, put a lot of effort into estimating the national statistics of overall forest biomass provided at the regional level. Furthermore, the INFN also provides data and information on tree species composition that would allow researchers to formulate potential scenarios on the chemical composition and thus availability of quantitative and qualitative percentages of lignin and cellulose. However, figures provided in the reports only show overall estimates of biomass from which it is not possible to calculate the volume of potential forest residues classes.

More accurate feedstock estimation would come from forest management plans. However, this type of information was not available at a regional level for Piedmont, Tuscany and Liguria. On the other hand, it is available in regions with an advanced forest management tradition such as the province of Trento. In the other Italian regions, the availability of reliable data depends on the forest owners if they have forest management plans or not. Private forest owners often have felling plans that do not allow for long-term estimates. In addition, only public and extensive forest properties such as those of Trentino allow to evaluate the biomass available at provincial or even regional level, while in many of the other Italian regions only consortia can allow forest management plans to be carried out since the territory is mostly private and highly fragmented.

The most accurate estimation of the available feedstock could come from a direct survey at the regional level carried out together with both forest harvesting companies and sawmills. The direct data can take into account not only local resources but also processed material imported from surrounding regions or even from abroad. At a national level, very few regions provide such estimation. The only data available could be found for the province of Trento that reported an annual potential of wood residues produced from sawmill chains in the entire province of 908,428 bulk cubic meters (bcm) $y^{-1}$ [62] (of which 65,408 bcm $y^{-1}$ is bark), all utilized for the production of energy. However, in the specific situation of Trentino, collecting data was more feasible compared to other regions because 76% of the forests in the Trentino province are of public ownership.

Unfortunately, data on sawmills residues are rarely available at the regional level also in the Alpine area. Some general data is available for three other regions: Piedmont, Liguria and Tuscany. However, in a study conducted in Italy, the potential availability of woody residues was estimated to be 12.67 million tons (about 23.5 million $m^3$) [63]. More recently, "Rapporto sullo stato delle foreste e del settore forestale in Italia" (RAF) published an estimated amount of chips of about 1 million $m^3$ [60], which is surely underestimated, and it shows again the need for reliable data on feedstock availability.

In Table 3 below, an estimation of chips from sawmills in Trentino province is shown.

**Table 3.** Amount of forest-wood chain residues in bulk cubic meter (bcm) [62] and conversion in $m^3$.

| Type of Biomass Residues (2G) Available from Sawmills in Trentino Province | Wood Residues | |
|---|---|---|
| | **bcm** | **$m^3$** |
| Bark | 65,408 | 46,720 |
| Woodchips | 410,501 | 293,215 |
| Sawdust | 392,502 | 280,359 |
| Trimmings | 40,017 | 28,584 |
| **Overall total residues** | **908,428** | **648,877** |

### 3.3.2. Tool for the Estimation of Forest Residues

Because of the unavailability of biomass data on wood residues from forests and sawmills, a quick search was conducted for articles recently published on the topic. Table 4 contains a compilation of the collected information. Despite the extreme heterogeneity of data, the results show that the available biomass residues from logging may range from 12% [59] to 47% [64] of the total harvested volume, depending on countries, forest site, wood species (conifers or broadleaves) and production end use. Wood residues in sawmills reach even up to 65% of the logged wood.

Considering bark as a valuable product, it would be even more important to know the bark content of processed logs. For this reason, some results regarding bark thickness are shown in Table 5.

### 3.3.3. Forest-Wood Chain Organization

Considering the organization of forest value chains for biorefineries, many other parameters need to be considered related to the supply chain in general. The model must be reconsidered in respect to the practices, which are specific of each region. Forest value chains are found throughout the entire country, but their structure, organization and work system differ according to the type of forests (high stand or coppice) and the commercial value of wood used. In northern Italy, where the presence of high stand forests (conifers and broad-leaved trees) is stronger, forest utilization focuses more on the production of sawn timber for wooden boards with high commercial value and sawing by-products that are sold for energy production. Instead, in central and southern Italy, where the ratio of coppice stands is larger, forest utilizations are more oriented on the production of firewood that is economically less valuable than sawn timber. The forest-wood chain in these regions needs to be totally reconsidered aiming for products with higher added value and utilizing residues that could be addressed to a biorefinery. Thus, geographical distribution and different forest types are issues to be considered when creating new value chains because the amount and the quality of the residuals greatly differs according to the initial feedstock.

**Table 4.** Availability of forest biomass residues from logging and sawmilling processes.

| Forest Biomasses Type Available at the Log Landing/Info | Percentages | Country/State | Comment/ Description | Source |
|---|---|---|---|---|
| Mixed beech forest (mainly with spruce, larch) | Residues 47–28% depending on forest sites | Slovenian sites | Indirectly calculated from net volume harvested | [64] |
| | Residues 65% | | Sawmills: unedged timber was sawn from the sawlogs, which comprised 35% of the total gross quantity of trees on average | |
| Forest biomass allocation | 88% Stems | Sweden, Germany, France and Finland | The calculated availability of biomass is affected by the type of potentials and constraints due to mechanization | [59] |
| | 12% Residues | | | |
| Softwoods: volume of tops and limbs | 17% of growing stock merchantable bole volume | Michigan, USA | | [65] |
| Hardwood: volume of tops and limbs | 29% of growing stock merchantable bole volume | | | |
| Forest residues | 15% of total biomass | EU average including 15 countries | Estimated forest harvest residues recovery rate | [66] |

The first step to be considered when developing biorefinery concepts is to raise awareness of the potentialities of innovation, which is not known by the most workers involved along the whole value chain.

In addition, there are other important parameters when establishing a forest biomass value chain. Regarding the standardization of measures, the moisture content of wood, which depends on many variables, must also be considered. An average water content of about 60% can be considered [72] for cut spruce in a wet state. Despite this, there are other studies that have estimated the residual wood moisture values of the cuts also varying between 112 to 180% in the same species [71]. In a biorefinery process, usually a hydric content of 30–40% referred to moist conditions (i.e., about 40.5–66.5% in the dry ones) is requested by the process. Furthermore, a biorefinery can work when at least 60% of the biomass is to be considered in a dry state.

Wood chips size is another relevant parameter to take into consideration. In the normal process along the value chain depending on the type of mechanization, the final size of the particles is quite variable. Usually, particles with a size over 63 mm are classified as oversized, while normal particles range from 3 to 63 mm and particles with a size < 3 mm are classified as fine. [73]. In pulp mills or biorefinery plants, the size of the particle is of importance because reducing the dimensions of the wood chips facilitates the penetration of chemicals, which enhances the delignification process [11]. On the other hand, chips smaller than 0.4 mm are less convenient because their absorption of chemicals is too high [74]. In a biorefinery based on anaerobic digestion, chip sizes between 10 and 30 mm are preferred [74].

**Table 5.** Thickness of bark from different European species, reported in cm or percentage (relatively to the total diameter of the stem).

| Tree Species | Percentage/ Thickness | Country/State | Comments | Source |
|---|---|---|---|---|
| Spruce | 1.5–2 cm | | Bark thickness increases with height of the tree | [67] |
| Poplar | 31.4–33.9% or 12.5–15.1% | Italy | SRC poplar (*Populus deltoides*) 2-year-old shoots vary in relation to moisture content, from 31.4% (fresh weight)–33.9% (dry weight) in large-sized DHB stems to 12.5% (fresh weight)–15.1% (dry weight) in smallest stems. | [68] |
| Birch | 0.33–0.98 cm | Republic of Karelia (Russia) | Harvested trees from felling. | [69] |
| Spruce | 0.31–0.39 cm | | | |
| Aspen | 0.53–1.82 cm | | | |
| Pine | 0.52–0.70 cm | | | |
| Scot pine | 3.02 cm | Eberswalde, Brandenburg (Germany) | The mean bark volume proportion was 5.6% and mean bark mass proportion was 3.3% | [70] |
| Spruce | 0.9–0.154 cm | Slovenia | Depending by the site, age | [71] |

In a pulp mill, wood is usually cut into thin chips with lengths of 15–20 mm, a thickness of 3–5 mm and a width below 20 mm. That means that chips in forest harvesting and in sawmills [73] need to be sized according to the envisaged process.

Finally, in the establishment of a supply chain, it is very important to use a common methodology to standardize the measurement units of the feedstock (chips). Although IS units should be used, wood is often traded using empirical measurement units such as the bcm. Table 6 shows the most frequent measurement units used according to the type of residue.

**Table 6.** Forest lignocellulosic biomass production chain and measurement units. * Quintals.

| | Forest Lignocellulosic Production Chains | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Forest Harvesting Enterprises | | | | Sawmills | | | Furniture and Window Frame Enterprises | |
| | Stem | Branches | Fuelwood | Woodchips | Bark | Sawdust | Trimmings | Sawdust | Trimmings |
| **Measurement unit** | $m^3$ | $m^3$; bcm | bcm | bcm | bcm; q * | bcm; q | bcm; q | q | q |

In addition, the conversion from bcm to cubic meters is a variable to consider because most of the chips sold at the land log are measured in bcm, and it is not always clear if biomass worked in biorefineries is measured in bcm or solid cubic $m^3$. Thus, this can sometimes generate confusion for the workers, at least in the first part of the value chain. However, bcm varies according to the type of wood species and geographical area. When converting bcm to $m^3$ and vice versa, the only parameter which influences the conversion is the chip size, but when the ton conversion occurs, bulk density and moisture content also have to be considered. As an example, Table 7 shows a comparison of correspondences between bcm and cubic meters compiled from different sources.

**Table 7.** Comparison cubic meters and bcm (beech, spruce and fir wood), compilation of sources.

| $m^3$ | bcm | Wood Type | Source |
|---|---|---|---|
| 1 | 1.4 | Logs | [75] |
| 1 | 2.5–3 | Wood chips | [76] |
| 1 | 5 | Chippings | [76] |
| 1 | 3 | Sawdust | [76] |
| 1 | 3.3 | Bark (not chipped) | [76] |

## 4. Economic Feasibility

The key question we need to address is if a forest biorefinery can be considered an opportunity for the rural areas or for the value chain as a whole. Currently, in Trentino province, all the production of bark and woodchips from forest harvesting is sold for power generation, either to DHPs or to CHPs, at a relatively low price because of the high content of humidity. Wood chips prices vary between EUR 8/bcm and EUR 16/bcm and sometimes can reach EUR 20/bcm in Trentino and surrounding Alpine regions [77].

In order to make a real feasibility study of the added value, the final product must be considered, too, not only lignin and cellulose, as well as the yield of the process because the price at which lignin or cellulose are sold depends not on their quality but also on the final end-use.

The future of chemical transformation in biorefineries is considered in building blocks such as xilitol, furfural, xylose syrup, levulinic acid and formic acid derived from hemicellulose, ethanol, lactic acid, sorbitol, nanocellulose from cellulose and vanillin and lignosulfunates from lignin [78], which are the products considered as the most promising in a biorefinery perspective since 2020.

It was estimated that in the process of ethanol production, 43% of lignin residue comprising 33% lignin by mass is at a minimum selling price of USD 43–70/t [13]. Kraft lignin shows the largest range of applications with middle and high value products. Low lignin purity ranges from USD 50–280/t, high purity lignin may reach USD 750/t. The price depends a lot on the amount which is produced by each plant [23]. Hodásová, et al. [10] and Tribot, et al. [23] report lignin prices of USD 260–500/t and lignosulfonates prices around USD 180–500/t, respectively. Soda lignin usually is sold at USD 200–300/t, while organosolv lignin prices range from USD 280 to 520/t.

The costs, which impact biorefinery production most, are related to logistics and transportation infrastructure and feedstock, which account for 40–60% of the final cost of biofuel production [79]. Facility location, capacity and technology selection for biomass to biofuel supply chains need to be carefully considered [79].

Recently, Laure, et al. [80] reported results on the conversion of 400,000 t of wood using the organosolv process. The authors showed that a competitive glucose price of EUR 218/t could be achieved when a revenue of EUR 325/t is obtained from the lignin and C5-sugar streams [80].

Other data that are still missing refer to the transport costs to the secondary treatment plants. Over a certain distance, indeed, the transportation costs would exceed the value of the secondary transformed products, and the process would not be convenient, whereas it was convenient to sell the biomass for energy production. Furthermore, environmental costs need to be considered and the distance of 200 km was reported as the threshold for transport.

The flowchart in Figure 3 shows the importance of biorefineries, which are able to transform the residues of the forest-wood chains into products with a high added value. As an example, from 20 t of softwood worth EUR 2000, it is possible to obtain more than

10 t of products with high added value, consisting of about 1.5 t of furfural with an average value of EUR 1500, 5.6 t of cellulose worth approximately EUR 4400, 3.6 t of lignin with an average value of about EUR 1200 and 0.7 t of resin (spruce) worth about EUR 70,000. Below, the prices of other biorefinery products are also reported (Table 8).

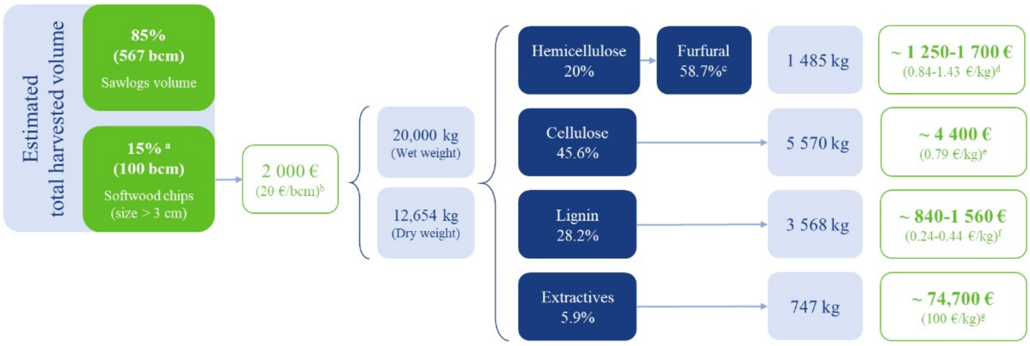


**Figure 3.** As an example, the flowchart summarizes yields and prices for different end products that can be obtained from softwood chips. [a] [81]; [b] [77]; [c] [82]; [d] Price of furfural: 1–1.7 USD/kg = 0.84–1.43 €/kg (Exchange rate = 1.19173, 12/04/2021 15:00—from Il Sole 24 Ore) [78]; [e] Price of cellulose pulp from wood: 791.19 €/t (March 2020) from https://www.indexmundi.com/commodities/?commodity=wood-pulp&months=120&currency=eur; [f] Organosolv lignin price: 280–520 USD/t [23]; [g] Average price of resin (spruce) on various retail websites (ETSY, Alibaba, Amazon . . . ): 100 €/kg (the price is higher, because it´s the retail and not wholesale price).

**Table 8.** Some prices of the most spread products of a biorefinery.

| Chemical | Price | Source |
|---|---|---|
| Ethanol | USD 0.37 USD/l | [16] |
| Kraft lignin | USD 260–500/t | [23] |
| Lignosulfonates | USD 180–500/t | [23] |
| Soda lignin | USD 200–300/t | [23] |
| Organosolv | USD 280–520/t | [23] |
| Furfural | USD 625/t | [83] |

## 5. Conclusions

Although bioeconomy and circular economy strategies contribute to the creation of a more environmental green economy, they require specific approaches in the transformation of forest-wood supply and processing chains in Italy. Actually, residues from forest harvesting and sawmills are used mainly for energy production in Italy. Innovative processing, such as in a biorefinery, needs to be encouraged, since wood and lignocellulosic biorefineries are not yet so widespread in southern Europe and even less in Italy.

The present article provides a review on the strengths and constraints in order to plan and rethink the forest-wood value chains aiming for a biorefinery perspective. It will be crucial to assess the availability (quantity and quality) of biomass supply and to not stress the forest and sawmill feedstock procurement looking for a biorefinery purpose.

An accurate estimation of biomass availability and supply is mandatory, and the values provided by forest inventories are not enough because they were collected with different purposes. Reliable and detailed data on forest wood residues available at regional levels are necessary, as well as the amount of residues from sawmill processing. Except for few regions (such as Trentino), no reliable data are available referred to forest harvesting residues and sawmills residues.

Forest management plans are among the main preliminary tools to be used to assess a raw feasibility for a forest biorefinery perspective. They are obligatory for public ownerships but not for private forest owners. This may become a constraint as the extreme fragmentation of national and especially private forest ownership prevents forest management planning and therefore drastically reduces the possibility of correct estimations. This aspect is crucial to forecast the future availability of residual woody biomass from cuttings and possible future variations in the supply chain. In addition, there are many sectors in the forest-wood value chain, such as carpentries and the wood industry, which are completely out of sight in the estimation of lignocellulosic biomass and that need to be counted on in the organization of a new tailored biorefinery.

The estimate of bark's quantity by wood species would be relevant as well to assess the presence of extractives because of a high amount of precious biochemicals.

Biorefinery processes have different yields, and the final products can vary a lot in chemical composition and reactivity. The value chains also need to he homogenized regarding the terminology of measurement units, which are one of the limitations to overcome. At the land log, the most common unit measure is bcm or the weight in tons or kg. Solid wood is measured in cubic meters. The conversion between the different unit is quite complex depending on moisture content, species and chip size. A feasible planning of new forest-wood transformation chains with high added value should consider multi-feedstock biorefineries and/or pilot plants able to process variable quantities of biomass starting from very low quantities such as 500 t/y.

Regarding the assessment of the real availability of wood residues, the article demonstrated that very few geographic regions in Italy are ready to implement new forest-wood value chains because they have all the necessary data. Trentino is surely one of the regions where it is possible to raise new awareness about the new opportunities of innovation because of the available forest management plans, a strong market related to wood and a high percentage of public ownership. Macro-regional cooperation could be pursued also in this perspective to test new value chains. Furthermore, the biorefinery perspective allows coping possible surplus of feedstock due to environmental stress events such as the windstorm Vaia in autumn 2018.

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