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Forest Supply Chain for Bioenergy: An Approach for Biomass Study in the Framework of a Circular Bioeconomy

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Abstract: To ensure the long-term viability of a circular bioeconomy based on native forests, it is crucial to enhance our understanding and overcome existing disparities in knowledge and application throughout the entire value chain of forest products. The objective of this article is to contribute towards this goal and facilitate the proper management of forest biomass. Firstly, a methodology is proposed for the study of biomass throughout the native forest value chain, identifying the main steps, criteria, and variables to consider. This approach is evaluated through a case study in Argentina, where over 2370 tons of biomass are wasted annually. A series of strategies for analyzing the most suitable uses and applications for this biomass are examined. Finally, some key approaches for the promotion of a circular and sustainable forest bioeconomy are identified. While it is true that there is still a long way to go before small rural economies can make a more efficient and comprehensive use of their resources (potentially including small biorefineries) with appropriate cascade use schemes, moving towards biomass energy use constitutes a practical and concrete alternative today. This proposal provides tools for accelerating this necessary ecological and energy transition.

Keywords: bio-based economy; biocircularity; biomass; bioenergy; native forests; sustainability

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1. Introduction

Biomass is currently among the most important potential sources of renewable energy in a global context of energy transition, the fight against climate change, and the search for regional and local alternatives to achieve sustainable development goals. Specifically, 90% of the total bioenergy used worldwide comes from solid biomass [1], with wood (67%), charcoal (7%), and other forest sector derivatives being the most widely used resources [2]. Additionally, a growing global demand for forest products is foreseen. These factors are the basis for the promotion of a circular bioeconomy [3].

In general terms, in the context of forest products, the concept of a circular bioeconomy emphasizes the effective and efficient use of forest resources from a life-cycle perspective (including the entire supply chain, from the forest to the different links of processing and the final use of wood and other raw materials extracted from it) through the cascading use strategy [4]. This strategy considers that the "ideal" final use of wood products, after having been reused or recycled as many times as possible, is usually energy recovery [4–6].

To ensure the long-term viability of a forest-based circular bioeconomy, it is crucial to bridge knowledge and application gaps along the entire forest products value chain [3], i.e., from biomass production or generation to each stage of industrial processing [7]. Each of these links generates forest residues, which must be minimized through efficient and sustainable forest management and finally used for energy generation, with potential secondary benefits for rural economies [6,8]. The promotion of small-scale bioenergy projects could play a key role in the sustainable utilization of these residues/resources and contribute to decentralizing the energy system [9]. It would also enable the development of new technologies on a smaller scale, strengthening local economies through the creation of value chains, including new businesses and small industries [10].

For Argentina, which has expansive forested areas, the forestry sector is a strategically important resource. In 2020, the timber industry recorded an annual turnover of more than USD 4.9 billion, accounting for 3.8% of Argentina's industrial value added. Additionally, it formally employs more than 110,000 people [11]. Forestry extractions mostly come from cultivated forests in the "litoral" (northeast of the country), which account for 92% of commercial timber production. Forestry based on native or indigenous forests, meanwhile, is concentrated in the provinces of northwestern Argentina (Chaco, Formosa, Santiago del Estero, Salta, and Jujuy), which together account for 80% of native forest production [12]. One-third of the total production of industrialized timber comes from these native forests. In this segment, 80% of production focuses on firewood and charcoal and, to a lesser extent, on the extraction of timber and the manufacture of basic wood products. Although the forestry sector in northwest Argentina makes a minor contribution to national trade, it is an activity that mobilizes the regional economy and has a high impact on local ecosystems.

According to recent estimates, the national forestry sector potentially generates around 36 million tons per year of dry biomass "in the field" (i.e., material that could be collected in the same place where it is generated), which is physically and legally accessible (91% from the native forest sector and 9% from forest plantations) [13]. However, these residues are highly diverse and spatially dispersed, and the lack of data on stocks and potential at the individual property level prevents their use [12]. On the other hand, the amount of biomass concentrated in forestry industries or processing centers, mainly in the "litoral", is estimated to be around 3.14 million dry tons per year [13]. It is difficult to determine the amount of waste that is generated from primary and secondary processing in individual forestry systems, as it will depend on the scale of sawmill production and the type of waste management and disposal systems. Furthermore, it is complex to study waste generation in value chains that are dependent on multi-diverse native forests such as those in north-western Argentina.

Without considering the traditional use of firewood for domestic heating, the use of native forest bioenergy has experienced minimal growth in Argentina despite its substantial potential. A major obstacle to its expansion is the lack of community support, especially for the use of indigenous forest by-products ("residues"), which are the main accessible source of biomass. Solving this challenge requires a coordinated effort between multiple levels [5,14], providing space for the participation of all sectors involved in forest product chains. It is also important to enable the generation and socialization of scientific-technical information that makes it possible to design alternatives that do not threaten natural capital now and in the future, while satisfying prevailing local demands. There are a few previous studies available on the subject [13,15,16], but none that facilitate an integrated approach to the circular bioeconomy.

Understandably, the more information that can be generated, the better the alternatives for integrated and efficient use of raw materials can be evaluated in a context of territorial planning and management that enables local development [3,10,17,18]. This process necessitates homogeneous and replicable methodologies that allow estimating the bioenergy potentials along the value chains of native forest biomass. The aim of this article is to contribute towards this objective and facilitate a better management of forest residues (resources). Firstly, a methodology is proposed to study biomass throughout the forest value chain, estimating the theoretical and technical potential of available bioenergy, and identifying the main steps, criteria, and variables to be considered. Given that bioenergy constitutes the last link in the framework of the circular bioeconomy, the analysis of the promotion of other uses and applications (biomaterials, chemical bio-inputs, or other bio-applications) is also discussed within this methodological framework. Likewise, the proposed methodological approach, which constitutes a contribution to the public policy discussion table, is evaluated by applying it to a case study of the timber sector in north-western Argentina. Finally, key aspects of native forest management that should be considered in the context of the promotion of a circular and sustainable forest bioeconomy are discussed and analyzed.

2. Materials and Methods

2.1. Methodological Proposal

The proposed methodological scheme is summarized in Figure 1. This diagram identifies the key aspects to be surveyed for the three main links in the forest chain to understand the potential biomass and its use. These are (i) production of forest biomass; (ii) primary processing of forest biomass (mainly saw milling); and (iii) secondary processing of forest biomass (industrial wood preparation) [3,4,6].

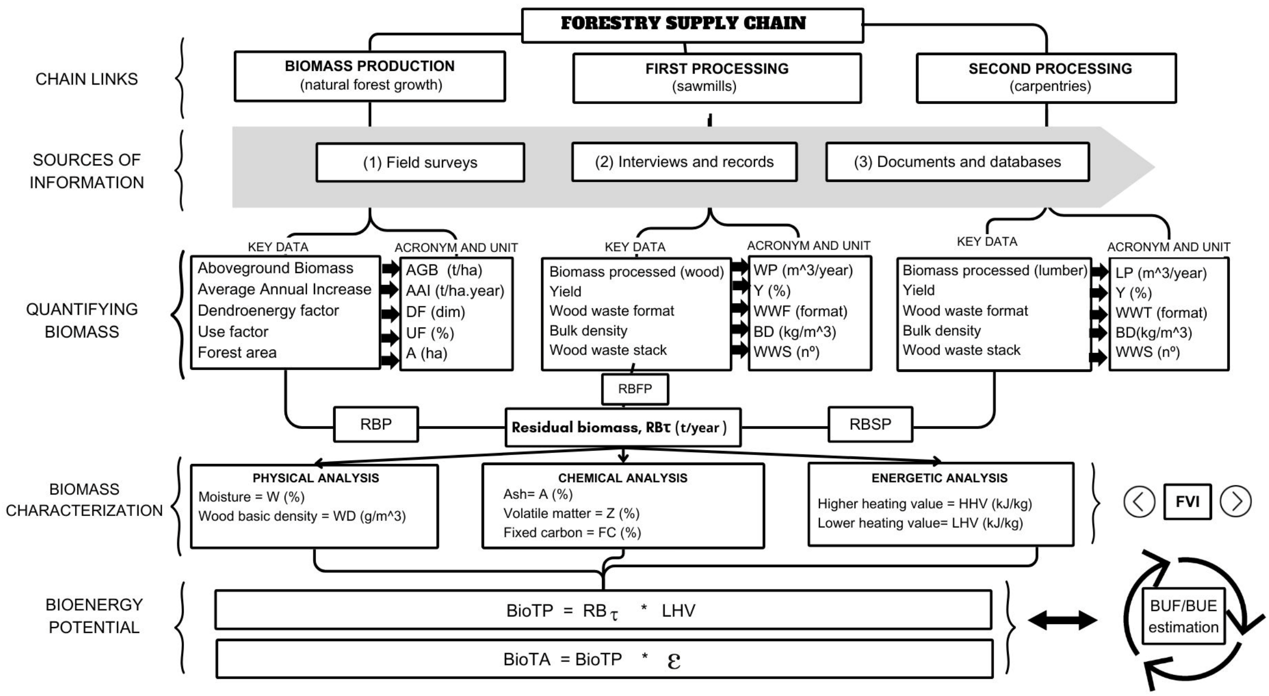

Figure 1. Methodology for the study of biomass generated along the forest chain. Source: own elaboration. Where: BioTP = theoretical bioenergy potential; BioTA = available technical bioenergy potential; RBP = residual biomass from production; RBFP = residual biomass from first transformation; RBSP = residual biomass from second transformation; RBτ = total residual biomass (t/year). See more detail in the text.

The basic criteria considered for the development of the proposal included:

(i.) The method was useful for replication in different native forest systems with the least amount of data and information (transitioning from arduous field work to prediction whenever possible [5,13,19]), to obtain comparative results in cross-sectional (between sites) and longitudinal (for a site over time) analyses.

(ii.) A valid picture ("diagnosis") could be obtained for the necessary dialogue between the multiple actors involved in forest value chains and the search for optimization of these systems [20].
(iii.) The parameters to be studied in each region could be easily monitored to observe the system's response to the implementation of new policies [6,21].

The outline in Figure 1 includes some of the main data collection tools (primary and secondary): personal interviews, field observations, satellite images, and existing raw records in public or private organizations in the territory. The literature published for the region is also an important source of data and information.

The core phase of the proposal includes three substages: (a) quantification of residual biomass; (b) characterization of residual biomass; and (c) estimation of the theoretical and technical potential of available bioenergy. However, the greater challenge is to find alternatives for the utilization of this forest biomass in relation to other possible uses that could be promoted within the framework of a sustainable circular bioeconomy. The use of lignocellulosic residues, which include cellulose, hemicellulose, and lignin, for a variety of bioproducts, bio-inputs, biomaterials, and other applications, are currently under study [22,23].

This proposal thus incorporates a second complementary phase to analyze the extent to which the forest chain meets the basic requirements for a circular forest bioeconomy: minimize the generation of bio-waste, prolong the use of biomaterials, and maximize the value of biomaterials and bioproducts consistently throughout their life cycle [24,25]. These principles are often encapsulated in the well-known phrase: "reduce, reuse, and recycle", which are fundamental steps, particularly when the raw material comes from native forests that provide multiple and invaluable ecosystem services [6,26]. To date, there are no standardized techniques to measure biocircularity, and the existing ones are in an incipient state of development and still require verification [23,27–29]. In this paper, two tools selected by European consortia for use and validation in the coming years [30] were applied, based on a prediction that they could constitute future reference points.

The following subsections detail each stage mentioned.

2.2. Biomass Quantification

2.2.1. Estimation of Residual Biomass from Production (RBP)

The evaluation of forest biomass along the value chain must necessarily begins with a study of the existing native resource or stock of aboveground biomass (AGB). In forestry plantations under harvesting, most owners have a forest inventory and know the volume of standing timber. From this database and the basic wood density (WD) of existing forest species, the AGB per tree (Equation (1)), per plot (adding the AGB of each tree within the plot) and per site (extrapolating to the total forest area) can be estimated [13,19]. However, if forest inventories exist, generally only the commercially valuable species of each region are included. To analyze the flow of residual biomass along the entire chain, it is important to approximate the total biomass present and the residual fraction that could potentially be used for other purposes. Therefore, all species should be included.

$$AGB\ (\mathrm{t}) = Vtotal\left(\mathrm{m}^3\right) * WD\left(\frac{\mathrm{t}}{\mathrm{m}^3}\right) \tag{1}$$

In this sense, through field sampling, it is possible to estimate AGB. AGB refers to the total amount of aboveground living organic matter in trees and shrubs ($\geq$1 cm dbh and height $\geq$ 50 cm) expressed in oven-dried tons per hectare. The following structural tree data are required: trunk height (from ground level to the first main branch), total height (from ground level to crown tip), and dbh (diameter at breast height, measured at 1.3 m from the ground) measured for all trees with dbh $\geq$ 10 cm (AGB_{10}) in each plot. The choice of a sampling method depends on the objective set, as well as the type of plots and their number. A general principle is that, for equal precision, the sample size should be larger the more variable the ecosystem under study, as in the case of multi-diverse native forests [5]. In general, a mean standard error of up to 20% on the estimated AGB at a confidence level of 90% is an acceptable value. From there, the AGB is estimated through the application of general allometric equations published in the literature or in databases such as GlobAllomeTree. The equations may be linear, potential, logarithmic, or polynomial, among others. In its simplest form, a simple linear regression can achieve a good fit (Equation (2)), where "a" is the intersection of the line, "b" its slope, and the residuals have a constant variance Var("ε") = σ^2, where AGB = aboveground biomass and D = dbh.

$$\ln(AGB) = a + b\ln(D) + \varepsilon \tag{2}$$

Once the AGB has been estimated at the plot level, it is possible to obtain average values by sectors, farms, or biomes [19,31]. Remote sensing allows estimating biomass at the landscape scale, but regardless of the sensor or satellite used, field measurements are essential to adjust the observed/measured relationships [31,32]. Likewise, working with satellite records is not within the reach of the common producer, and therefore their use is more restricted.

Importantly, if the stands are subject to forest management, with the application of silvicultural practices such as pruning, liberation thinning, and improvement cuts, these should be considered when estimating the AGB per plot [5]. In other words, each type of management practice will leave a fraction of the AGB available per year, contributing to the total biomass available for each plot. In the case of forests with minimal or no silvicultural practices, these values are difficult to estimate.

It is also necessary to evaluate the annual growth fraction (AAI) of the forest per year (which would represent the "annual interest" gained), and by applying use coefficients (utilization factor, UF, expressed as a percentage of the AAI) and safeguarding the organic cycle (dendroenergetic fraction factor, DF), as well as other uses, it will be possible to know how much annual biomass could be harvested for bioenergy purposes. The DF indicates the portion of total biomass that would remain for soil protection. In native forests under harvesting, the value of the volumes extracted for timber should be discounted (which would be equal to the value of raw material consumption from the forestry-industrial sector), and if there are other uses of wood (timber and non-timber), the portion demanded for all applications identified through preliminary research should be discounted [13].

2.2.2. Estimation of Residual Biomass from First (RBFP) and Second Processing (RBSP)

The biomass that transitions to the next link in the production chain is the biomass of timber interest, that is, the trunk or shaft of the tree (consumption of raw material). Here, it is necessary to consider how much processed biomass (volume of wood, in m^3 per year) enters the processing establishments for its first transformation (basically sawing) and how many final products are obtained (volume of products, in m^3 per year); this corresponds to the yield (Equation (3)). The remaining unused portion (RBFP) is the one that could have a bioenergy potential.

$$\gamma_{BFP}\,(\%) = \frac{Vl\ \left(\frac{m^3}{yr}\right)}{Vw\ \left(\frac{m^3}{yr}\right)} * 100 \tag{3}$$

where:

γ_{BFP} = yield biomass from first processing (%);
Vl = finished lumber volume (m^3/yr);
Vw = biomass processed volume (wood) (m^3/yr).

For the next industrial link, the biomass residual fraction could be estimated grossly, knowing the yield with which the *Vl* (m^3) that enters from the previous stage is processed. The same procedure already used will be necessary for the estimation of RBSP (Equation (4)):

$$\gamma_{BSP}\ (\%) = \frac{Vp\ \ (\frac{m^3}{yr})}{Vl\ (\frac{m^3}{yr})}\ *\ 100 \tag{4}$$

where:

γ_{BSP} = yield from biomass second processing (%);
Vp = finished products volume (m^3/yr);
Vl = finished lumber volume (m^3/yr).

We have the annual residual biomass volume (VT, m^3/year) that could be utilized for energy purposes from industrial stage (that is, RBFP + RBSP). However, for a more precise estimate, since the waste has different formats (sawdust, chips, shavings, bark, etc.), it is necessary to quantify the dry weight of each residual format and then add all those categories. To do this, the type and bulk density (t/m^3) of each format are defined. For smaller waste (sawdust for example), the bulk density will be estimated in terms of the number of piles or bundles. For larger waste, the transport density should be estimated. It is recommended to use the solid biofuel categories defined in the international standards (please see Table S1). In other cases, when basic information is scarce or difficult to obtain, it may be sufficient to estimate the participation (*Pi*) of each biomass format to the total volume (VT), according to the local wood flow diagram, and then sum up the combined contribution of all these formats to estimate RBτ (Equation (5)) from industrial sector. For example, of the 100% that enters the first transformation, it is possible to define the percentage that is destined for sawn timber (from which sawdust will be obtained as waste), the percentage that is destined for the manufacture of packaging or low value-added products (from which chips, solid waste, etc. will be obtained), and the percentage that will be destined for higher value-added products such as furniture and openings, etc. (where mostly chips will be generated). Although the formats in which the residual biomass is presented in each establishment are not homogeneous, as mentioned above, for the purpose of quantifying the amount residual biomass a single format can be assumed as the most representative.

$$RB\tau\left(\frac{t}{yr}\right) = \sum\nolimits_{i=\alpha}^{n} Q_i\left(\frac{t}{yr}\right) = VT\left(\frac{m_3}{yr}\right)\ *\ P_i\left(\frac{\%}{100}\right)\ *\ BD_i\ (\frac{t}{m_3}) \tag{5}$$

where:

$RB\tau$ = total residual biomass (t/year).
Q_i = quantity of each biomass format (t/year).
i = each biomass format (sawdust, chips, shavings, etc.). They are identified with Greek letters (α, β, etc.).
VT = biomass waste annual volume from industrial sector (m^3/year).
P_i = share of each biomass format to the VT (%/100).
BD_i = bulk density of each biomass format (t/m^3).

2.3. Biomass Characterization

International standards for estimating bulk density, physical, chemical, or energy properties, and the characteristics and quality of solid biofuels can be found in the Supplementary Materials (Table S1). It is worth mentioning the importance of the following estimates, which are included in the Fuel Value Index (FVI, Equation (6)) [33]: moisture (%); ash (%); volatile matter (%); fixed carbon (%), and calorific value (kJ/kg). In general terms, it is advantageous to use dry biomass, since its transport cost is lower, its milling is simpler, and it has a higher heating value. Indeed, for each kg of water, 2.4 MJ of energy is needed to evaporate it. Likewise, the higher the ash content, the lower its combustible quality. The factors that increase the quality of the material from the energy point of view are the multiplicative factors of the numerator of Equation (6). Likewise, the characterization is important in view of defining the type of process and technological systems that will be used for energy conversion if this choice is available.

$$FVI\left(\frac{\mathrm{kJ}}{\mathrm{cm}^3}\right) = \frac{LHV\left(\frac{\mathrm{kJ}}{\mathrm{g}}\right) * WBD\left(\frac{\mathrm{g}}{\mathrm{cm}^3}\right)}{Z\left(\frac{\mathrm{g}}{\mathrm{g}}\right) * W\left(\frac{\mathrm{g}}{\mathrm{g}}\right)} \quad (6)$$

where:

FVI = fuelwood value index ($\mathrm{kJ/cm^3}$).
LHV = lower heating value, on a dry basis (kJ/g).
WBD = wood basic density, on a dry basis ($\mathrm{g/cm^3}$).
Z = ash content, on a dry basis (g/g).
W = moisture content, on a wet basis (g/g).

2.4. Theoretical and Technical Bioenergy Potential Estimation

In general terms, the biomass and bioenergy potential of a territory can be classified into different categories [34–37]: theoretical potential (BioTP), technical potential (BioTA), and sustainable implementation (BioSI) (Equations (7)–(9)). Not all the potential biomass identified at a site can be utilized due to various kinds of constraints that define different harvesting potentials (Figure 2).

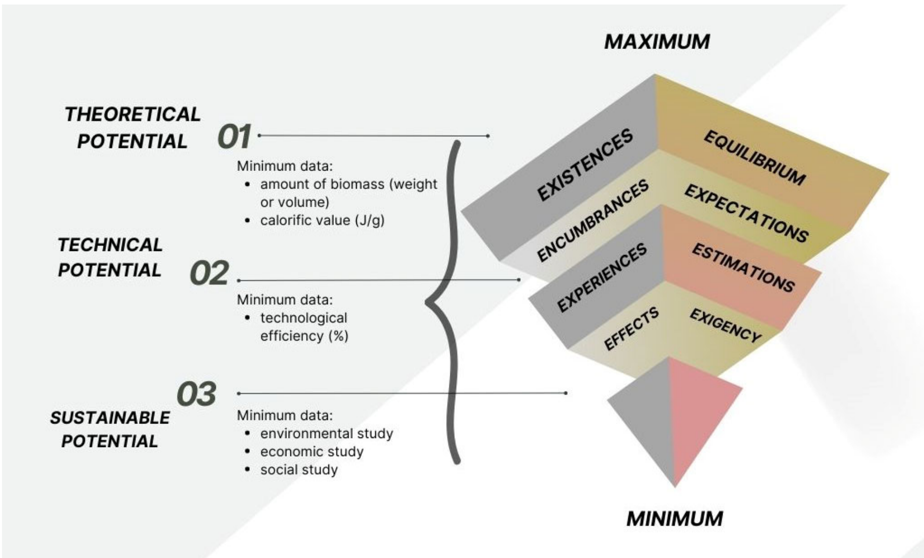

Figure 2. Inverted pyramid approach to approximate bioenergy potential. Source: own.

When sizing a complex system or investing in infrastructure, failing to consider the potential of the resource can lead to over-sizing and extra costs and/or the generation of negative impacts on the site. The theoretical potential bioenergy (BioTP), which is determined by biophysical basis, i.e., type and amount of biomass and caloric potential (LHV), marks the starting point of any bioenergy project (Figure 2). When it comes to biomass generated in the field, it is necessary to consider how much biomass is obtained per unit of area. For a known area where the biomass of interest is generated, the BioTP can be calculated according to Equation (7), where Q is biomass quantity:

$$BioTP\,(\mathrm{MJ{\cdot}yr^{-1}}) = Q\ (\mathrm{t{\cdot}yr^{-1}}) * LHV\ (\mathrm{MJ{\cdot}t^{-1}}) \quad (7)$$

The technical potential available (BioTA) can be preliminarily estimated as the BioTP times the conversion efficiency (ε) of the specific technology to be used, depending on the required energy application (heat, electricity, mechanical energy, etc.) (Equation (8)).

$$BioTA\ (\mathrm{MJ{\cdot}yr^{-1}}) = BioTP\ (\mathrm{MJ{\cdot}yr^{-1}})\ *\ \varepsilon(\%) \quad (8)$$

Finally, the potential for sustainable implementation (BioSI) will include a subfraction of the technical potential (BioTA) that can be harvested in an economically viable, socially acceptable, and environmentally appropriate manner (Equation (9)).

$$BioSI\ (\mathrm{MJ{\cdot}yr^{-1}}) = BioTA\ (\mathrm{MJ{\cdot}yr^{-1}})\ *\ c1\ *\ c2\ *\ c3\ldots \quad (9)$$

Some of the criteria (called $c1$, $c2$, $c3$, ...) to be considered to define this fraction are shown in Figure 2 and are described in [20] as "the 8 E's", including aspects such as existences, equilibrium, encumbrances, expectations, experiences, estimations, effects, and demands. Other locally defined criteria can be used. This undoubtedly implies the development of a specific study that is beyond the scope of this article, which is limited to the application of BioTP and BioTA.

2.5. Forest Value Chain: Biocircularity Analysis

The possible routes considered for the waste biomass under study in the framework of a circular bioeconomy are shown in Figure 3 (modified from [38]) and are summarized as follows: bio-applications (food or feed, e.g., BFF), bio-based products (chemical compounds or materials of interest, BBP), or bioenergy (BIO). The BBP category offers unique potential for additional applications, either through direct reuse or recycling. This differentiates it from other use options, as it allows for sequential and continuous utilization of the initial feedstock [27,28,38]. In the scheme of the cascading use of waste biomass resources, utilizing them in multiple applications before deriving them as energy will be a challenge for the coming decades [3,29,39,40].

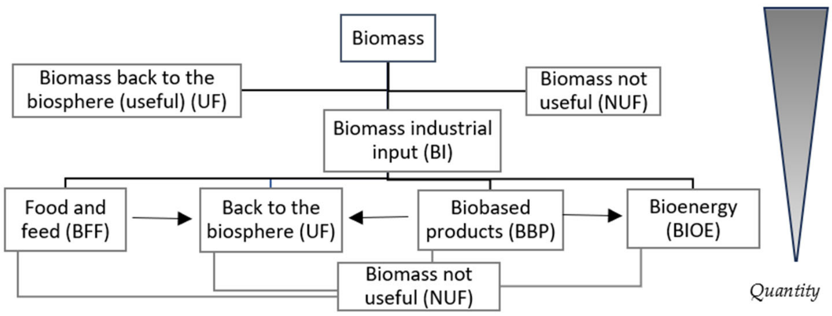

Figure 3. Diagram of possible routes of forest biomass within a value chain. The BBP category is the only application that will allow several uses of the feedstock in a cascading scheme. Source: Modified from [38].

To meet the objectives of the circular bioeconomy, it is imperative to develop approaches to assess and verify the circular characteristics of bio-based materials, products, or sectors [23,41]. The BUF (Biomass Utilization Factor) developed and applied in the framework of German and European projects [4] quantifies how much (production efficiency) and how often (cascading use) biomass is used in a value chain of bio-based products or in a whole sector [27,38]. It is a simple tool that can be understood and applied in different sectors, although it must still be validated for specific applications. This makes it possible to evaluate the cycle followed by the biomass entering the industrial process (BI_0, which would be the 100% under analysis). Many of the steps explained above are fundamental for the application of this indicator: (i) description of the forest supply chain under analysis and its context, defining the limits of the system under study; (ii) data collection and modeling hypotheses; and (iii) application of the BUF. As a last step of the method, it is possible to carry out scenario analyses based on public policies that could be applied in the specific case under study, to verify the direction and magnitude of the response through the BUF.

The application of the BUF basically involves, for each chain stage of the system under analysis, solving for the product of BI (initial biomass of the stage) and the production efficiency (PE) at that stage (i.e., in the forest supply chain, how much raw material is harvested (wood), how much is lost, and how much could be used for bioenergy or other non-energy applications, passing through to the next level of the cascade) (e.g., Equations (10) and (11)). A full explanation can be found in [38].

$$BUF_0 = BI_0 \, * \, PE_0 \tag{10}$$

where:

BUF_0 = Biomass Utilization Factor (BUF) for the starting stage 0 (%)

BI_0 = 1 ≙ total biomass entering the industrial process (which corresponds to 100%) (mass flows on dry matter basis)

PE_0 = production efficiency in the cascading stage 0 (%).

$$PE_0 = \frac{(BBP_0 + BIO_0 + BFF_0 + UF_0)}{100} \tag{11}$$

The calculation of the following cascade stages will use the same Equation (10) but considering the BUF obtained in the previous stage. Specifically, since the BBP is the only alternative from Figure 3 that allows for cascade production with different products that can be obtained, used, and reused, the determination of the biomass available in the next stage will be based only on the fraction that corresponds to the BBP in the previous stage. This calculation will result in a total BUF at the end of the last cascade stage. For cascading use, the BUF is typically >1 and can reach >2 or more if the material can be reused in several stages. This is the first scientific article that uses this indicator for a concrete case study: the forestry sector in Argentina.

2.6. Potential Chemical Applications of Biomass

Forest residues can be used to obtain chemical compounds. The biomass utilization efficiency (BUE) indicator can be used to evaluate and compare conversion processes and final bioproducts from biomass [29]. Similar and complementary to BUF, BUE shows the efficiency with which biomass is utilized when chemically transformed. BUE is hereafter defined as the percentage of initial biomass that ends up in the final product (P) based on the molar mass of the reactant (R = biomass) and the target bioproduct (P = bioproduct). The BUE can be further subdivided into four specific categories: BUE_S, BUE_L, BUE_H, and BUE_E (Equations (12)–(15)). Further details of the method can be found in [29].

$$BUE_S = \frac{RMM_P^{biomass} \, * \, ideal \; moles_P}{\sum (RMM_R^{biomass}) \, * \, ideal \; moles_R} \tag{12}$$

$$BUE_S = \frac{Biobased \; content_P \, * \, RMM_p \, * \, ideal \; moles_P}{\sum (RMM_R^{biomass}) \, * \, ideal \; moles_R} \tag{13}$$

where:

BUE_S = BUE stoichiometric. Amount of biomass incorporated in the product (according to stoichiometric limit). It is expressed as a percentage;

RMM = relative molecular mass (g·mol^{-1}) = $RMM_{biomass}$ + RMM_{other};

M = mass of a substance or feedstock (g) = $M_{biomass}$ + M_{other};

$RMM_{biomass}$ and $M_{biomass}$ = biomass components;

RMM_{other} + M_{other} = non-biomass components;

$$BUE_{H/L} = \frac{RMM_P^{biomass} * ideal\ moles_P}{\sum(RMM_R^{biomass}) * ideal\ moles_R} * Yield_P \quad (14)$$

$$BUE_E = \frac{HVV_P^{biomass}}{RMM_R^{biomass} * HHV_R^{biomass}} * 100 \quad (15)$$

where:

BUE_L = BUE lowest. Realistic amount of biomass (lowest) that can feasibly be incorporated into the final product based on current yields for the chemical conversion route described. Input from literature and industry experts is required.

BUE_H = BUE highest. Realistic amount of biomass (highest) that is feasible to be incorporated into the final product based on current yields for the described synthesis route. Input from literature and industry experts needs to be explored.

BUE_E = BUE energetic. It is defined as the HHV (higher heating value) of the product divided by the HHV of the reactant (kJ·g^{-1}).

This approach completes the proposed analysis, giving an a priori idea of the resource's potential. The only inputs required to calculate the BUE are the kind of biomass, the chemical equation of its transformation, the efficiency of the process (in the case of BUE_L and BUE_H), and the target bioproduct. Given the current trends of increasing economic and material competition for resources, an increased demand for the identification of these types of alternatives can be expected [1,5,25].

3. Case Study Description

The Caimancito Forest Basin (CBF) in Jujuy, Argentina [15], also called "Polo de Santa Bárbara" [15,16], includes the departments of Ledesma (municipalities of Caimancito, Calilegua, Fraile Pintado, Libertador General San Martín, and Yuto) and Santa Bárbara (municipalities of El Talar, Palma Sola, and Santa Clara). Forest basins are defined as geographic spaces where there is a marked presence of native forest and actors that work on the harvesting, transformation, and commercialization of timber and non-timber products [42]. It is therefore a planning tool at the landscape or regional level to establish an integral scheme of the territory, within which the vocation of use, the sustainable provision of ecosystem goods and services, and the conservation of natural and cultural resources are considered.

The CBF covers an area of more than 740,000 ha (14.5% of the provincial territory) and is home to 15% of the provincial population (nearly 100,000 inhabitants [43]), including in 32 native communities belonging to the Guaraní, Kolla, and Ocloya ethnic groups. It has some of the worst social indicators in the province in terms of UBNs (unsatisfied basic needs), access to household services, education, and receipt of ordinary pensions [44]. Two main ecoregions are identified in the CBF: Southern Andean Yungas (SAY), covering more than 60% of the basin (Tropical and Subtropical Moist Broadleaf Forests biomes), and Dry Chaco (DC), with less than 13% (Tropical and Subtropical Grasslands, Savannas and Shrublands biomes) [45], while the remaining surface corresponds to cattle pastures, wetlands, forest plantations, and urban areas. The relief is mountainous, with alternating mountain ranges and valleys in a general north–south direction, and the average altitudes of the sectors under exploitation are around 500–800 m.a.s.l. The climate is generally warm and humid (subtropical), with a dry season between April and October and torrential rains during the rest of the year that total between 600 and 1400 mm per year. Average annual temperatures range between 18.7 °C and 22.4 °C, with a minimum of 14 °C in July and a maximum of 26.8 °C in January for the town of Caimancito [46].

This region has the highest demand for wood from native forests in the province, consuming 70% of the total industrialized production [15,16]. The following species are mainly used: *Anadenanthera colubrina* (Vell.) Brenan, *Calycophyllum multiflorum* Griseb, *Cordia trichotoma* (Vell.) Arráb. ex Steud., *Cedrela balansae* C.DC., *Myroxylon peruiferum* L.f, *Astronium urundeuva* Engl., *Handroanthus impetiginosus* (Mart. ex DC.) Mattos, *Parapiptadenia excelsa* (Griseb.) Burkart, and *Phyllostylon rhamnoides* (J.Poiss.) Taub. Native woods are harvested without specific management (except for a minimum cutting diameter for those considered valuable woods, according to [47]), with a level of informality that exceeds 90% and obsolete technology for cutting and remanufacturing [12]. Most of the SAY lowland sectors have been replaced by agricultural crops, and the remaining forests have been severely degraded by successive forest harvesting—which has practically exhausted the timber stocks of valuable species—as well as by forest fires and cattle ranching [15]. Raw material (wood) is increasingly scarce [15,16].

The forestry activity in the sector is articulated by different links between the forest and the final consumers. At the industrial level, more than 90% of sawmills are included in the category of "micro-industries" (≤940 m^3/year) and the rest are "small industries" (>940 and ≤4720 m^3/year), according to their scale of production (sum of the volume of the different products sawn and manufactured by each establishment in m^3/year) [48,49]. In many cases, the sawmills themselves have incorporated the carpentry sector into the production line to add greater value to their products. Therefore, the estimation of BioTP and BioTA was carried out in two phases: (i) field link and (ii) industrial links. Ongoing research in the study area will soon provide more information.

4. Results and Discussion

4.1. Forest Biomass, BioTP, and BioTA

Table 1 summarize the values used for each of the parameters of the method and the results obtained for the case under study. The weight values (tons) refer to dry matter.

Table 1. List of assumed values for each parameter for CFB, Argentina.

Acronym	Meaning	Unit	Value	Reference
	Stage 1 (biomass production)			
A	Forested area in the basin	ha	518,000	[15]
AGB	Aboveground wood biomass	t/ha	138.82	[50,51]
AAI min	Average annual increase (minimum rate)	t/ha·year	2.78	[13,31]
AAI max	Average annual increase (maximum rate)	t/ha·year	5.55	[13,31]
Wood consumption	Amount of raw material (wood) consumed by the forestry industry	m^3/year	13,801 *	[16]
DF	Dendroenergetic factor	adim	0.85	[13,31]
UF	Utilization factor	%	0.5	[52]
CF	Caution factor	%	50	This work
BAAIm	Minimum amount of biomass grown annually	t/year	603,880	This work
BAAIx	Maximum amount of biomass grown annually	t/year	1,215,089	This work
RBP min	Residual biomass from production (minimum)	t/year	301,939	This work
RBP max	Residual biomass from production (maximum)	t/year	607,545	This work
$LHV_{20\%}$	Lower heating value, on wet basis (20%)	GJ/t	14.644	[53]
	Stage 2 (industry)			
Vw	Biomass processed (wood volume)	m^3/year	13,801	[16]
Production	Sum of the volume produced of the different wood products sawn and manufactured by each establishment in the forest basin	m^3/year	6021	[16]
Y	yield	%	43.6	[16]

Table 1. *Cont.*

Acronym	Meaning	Unit	Value	Reference
WWF	wood waste format	format	α = sawdust, β = chips/crushed fuels, γ = wood trimmings and δ = shavings	(Table S1)
RBFP + RBSP	first and second processing residual biomass	t/year	2370	This work
$LHV_{0\%}$	Lower heating value, on dry basis (0%).	GJ/t	16.35	This work
A	Ash	g/g	0.030	This work
W	Moisture	g/g	0.105	This work

* The census detected 30 sawmills, with a coverage error of 5%.

Given that there is a lack of in-depth studies that consider topographic, environmental, legal, and other criteria, a caution factor (CF) of 50% is used. The AGB was calculated indirectly from current aboveground and belowground woody carbon [50] with a carbon fraction of 0.47 [51]. Direct on-the-ground measurements will allow this information to be specified. According to these estimates, the total biomass annually available from CBF for bioenergy would range from 300,000 t/year to 600,000 t/year (dry matter), but it may be lower given the general state of degradation of the forests. The BioTP would range from 9 to 18 MGJ/year.

The caloric potential of biomass was expressed as useful energy, considering two possible energy applications: heat generation by means of devices such as boilers ($BioTA_t$) with three possible thermal yields [54] (75%, 80%, 90%); and electricity generation ($BioTA_e$) by means of mature technologies such as steam turbines and combustion. Combustion remains the most widely used thermochemical conversion pathway for electricity generation because its investment costs are lower than those of other technologies and it is easier to implement. Three conversion efficiency values reported in the literature were used: 18%, 20%, and 25% [40,55,56]. Figure 4 (which takes the typical inverted pyramid shape already shown at the theoretical level in Figure 2) represents these potentials, considering the following:

- BioTP: average value between the estimated maximum and minimum (in GJ/year).
- $BioTA_t$ (thermal): average value between the three conversion efficiencies (75, 80, and 90%).
- $BioTA_e$ (electrical): average value between the three conversion efficiencies (18, 20, and 25%).

As can be clearly seen in Figure 4, the $BioTA_e$ available for electricity generation is one-fifth of the BioTP and one-fourth of the $BioTA_t$ for thermal uses. Clearly, these estimates must be complemented with specific studies to advance towards the definition of BioSI. In other words, these estimates lack validity if they are detached from the context from which they were obtained, particularly in the case of native forests [21]. It is therefore imperative to complement these approaches with the inclusion of sustainability criteria, to define a BioSI that simultaneously fulfils the multiple territorial objectives in a land-use planning scheme while ensuring the sustainability of natural capital and ecosystem services in the long term [17].

4.2. Industrial Biomass, BioTP and BioTA

The demand for wood within the forest basin is 13,801 m^3/year, and the production level is 6021 m^3/year [16]. This implies a yield of 43.6% (Table 1). The volume in the province is calculated considering the log as a perfect cylinder, taking only the diameter at the fine tip by the length of the log [48]. Table 2 shows an overview of the characterization of forest residues from the industrial stage. According to the industrial flow in the study area, waste generation is assumed as follows [16]: 67% sawdust (type α) from sawn wood; 29% from wood for packaging in the form of chips (12%, type β) and wood trimmings

(17%, type γ); and 4% from furniture construction in the form of shavings (type δ). The estimated weight and other characteristics of these residues are shown in Table 2. The HHV was obtained in the laboratory using a Parr Model 1341 oxygen bomb calorimeter. Three samples of each of the four types of materials (α, β, γ, δ) were taken and analyzed in duplicate. Average values are shown in Table 1 (stage 2, industry), as well as for ash content (%) and moisture (according to international standards, Table S1). The results of a more intensive sampling progress would allow us to specify these values with greater statistical robustness. Bulk density data were obtained assuming the average values reported in defined in the international standards (please see Table S1) for each material type.

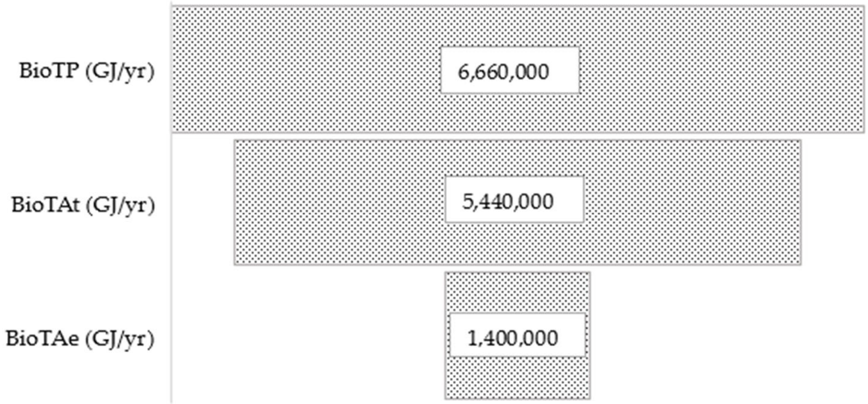

Figure 4. Bioenergy potential in the CFB from the field link (forest or biomass production). Where: BioTP = theoretical potential (average between minimum and maximum estimated, in GJ/year); $BioTA_t$ = available technical potential for thermal purposes (average between the three defined conversion efficiencies, in GJ/year) and $BioTA_e$ = available technical potential for electrical purposes (average between the three defined conversion efficiencies, in GJ/year).

Table 2. Characterization of forest residues from the industrial stage. The FVI was estimated based on lower heating value, ash, and moisture on a dry basis. Where: tDM = tons of dry matter per apparent cubic meter.

Format (Type)	Nomenclature	Comes From	Size	Participation	Bulk Density	Quantity	Fuelwood Value Index
			S	P	BD	Q	FVI
			mm	(%)	(tDM/m^3 Apparent)	(tDM/year)	(kJ/cm^3)
Sawdust	α	Cut with sharp tools	1–5 mm	67	0.300	1563.8	1557
Chips/crushed wood fuels	β	Cut with sharp tools or shredded	5–100 mm	12	0.250	233.4	1298
Wood trimmings	γ	Cut with sharp tools	50–150 mm	17	0.380	502.58	1972
Shavings	δ	Wood planing with sharp tools	1–30 mm	4	0.225	70.02	1168

The FVI indicates the quality of each residue format. From highest to lowest: solid wood trimmings (FVI = 1972), followed by sawdust, chips and crushed wood fuel, and lastly shavings (1168) (Table 2). According to the above definitions, 2370 tDM of total industrial level residual biomass (RBFP + RBSP) would be obtained, considering the bulk density of each type of material. The BioTP at the CFB (considering 30 similar establishments) would be approximately 38,700 GJ/year. Estimates of thermal and electrical energy applications for identical efficiency values are shown in Figure 5.

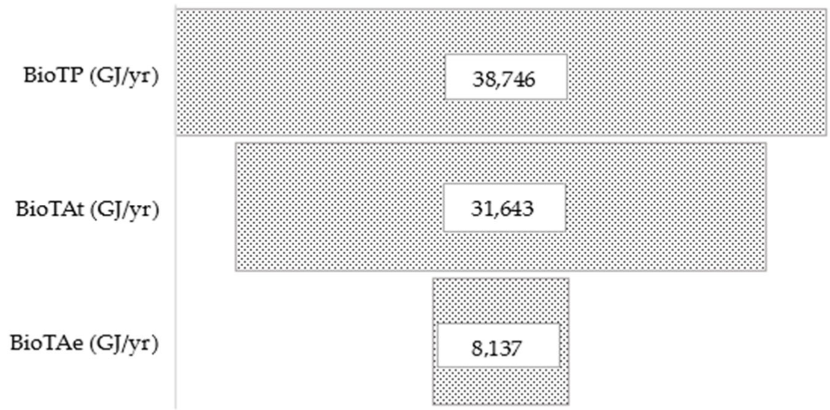

Figure 5. Bioenergy potential in the CFB from the forestry-industrial link. Where: BioTP = theoretical bioenergy potential (in GJ/year); $BioTA_t$ = technical bioenergy potential for thermal purposes (in GJ/year) and $BioTA_e$ = available technical bioenergy potential for electrical purposes (in GJ/year).

Future scientific and technological improvements will no doubt increase the efficiency in the use of forest resources. Likewise, the formation of new local capacities can contribute to ensuring that new techniques and technologies can be easily incorporated, making it possible to generate income alternatives at the territorial level and helping to anchor the population in rural areas.

To verify the model usefulness in different regions, introduce comparable results, and make them freely available, it would be interesting to evaluate the development of GIS (Geographic Information Systems) support as a complement [13,30].

4.3. Biomass Use in the Forest Value Chain: Biocircularity

The residual biomass analyzed in this section corresponds only to that which is available from the industrial stage (the biomass from the field link is not included). The objective of this stage of analysis is to reflect on the current situation of the CBF and the potential for generating increasingly positive biocircularity indicators, implying a higher local benefit. Beyond the baseline BUF value obtained, the greatest utility lies in the possibility of analyzing whether the introduction of a certain policy could improve its performance. Therefore, given that sufficient information has been collected in the previous stages to characterize the current situation (baseline), four alternative scenarios were proposed based on simple changes in forest residual biomass management. The resulting five scenarios are summarized in Table A1 (Appendix A): the current scenario (SC0 = without the use of bioenergy) and four others with various uses of bioenergy.

The alternative scenarios show increasing levels of optimization, introducing a new variant in each case to observe how this influences the value of each indicator [27,38]. Values assumed for the BUF in baseline and alternative scenarios are showed in Table 3. It is worth mentioning that 100% of the biomass is assumed to enter the industrial process (saw milling). The difference between the residual biomass that remains in the field and is not collected and that which arrives at the sawmill implies a loss of more than 40% of the material [49]. More detailed studies are needed to adjust these values. Likewise, other values taken from the literature with regards to wood conversion efficiency should be updated for the type and scale of the industry, type of raw material, and characteristics of the equipment, machinery, and labor of each industry.

As shown in Figure 6, the baseline scenario (SC0) is the worst performing in a biocircularity analysis, with a BUF value of 0.81. When introducing the use of bioenergy (using residual biomass) in the subsequent scenarios, the value indicator increases up to 1.52 in the last scenario. This value is like that found by [38] for completely different starting scenario characteristics. In this sense, the indicator should be handled with caution since it logically masks the context details. Its usefulness lies in its integration with the information collected in the main phase of the methodological proposal presented here, which allows for its correct interpretation.

Table 3. Values assumed for the Biomass Utilization Factor (BUF) in baseline and alternative scenarios. The scenarios are described in the footer and Appendix A [1]. The acronyms were defined in Figure 3 and correspond to the following: BBP = bio-based products; BIO = bioenergy; UF = biomass back to the biosphere (useful); NUF = biomass not useful.

	SC0		SCBI		SCBII		SCBIII		SCBIV	
	Unit	**Value**	**Unit**	**Value**	**Unit**	**Value**	**Unit**	**Value**	**Unit**	**Value**
					Stage 1					
BBP	%	43.7	%	43.7	%	58.7	%	58.7	%	58.7
BIO	%	0	%	31.3	%	16.30	%	26.3	%	26.3
UF	%	5	%	5	%	5	%	5	%	5
NUF	%	51	%	20	%	20	%	10	%	10
					Stage 2					
BBP	%	70	%	70	%	70	%	70	%	70
BIO	%	0	%	5	%	5	%	15	%	15
UF	%	5	%	5	%	5	%	5	%	5
NUF	%	25	%	20	%	20	%	10	%	10
					Stage 3					
BBP									%	8
BIO									%	5
NUF									%	87

[1] Where: SC0 = current situation in the CBF, with no bioenergy use and recovery of 10% of by-products (UF) between stages 1 and 2 (5 and 5% respectively); SCBI = equal to SC0 but with bioenergy use of a large part of NUF (the unused fraction), which is reduced from 51% to 20% (stage 1) and from 25% to 20% (stage 2)); SCBII = equal to SCBI + 15% improvement in feedstock utilization efficiency (BBP) in stage 1 of the cascade, with respect to the baseline scenario (SC0); SCBIII = equal to SCBII + new NUF reduction by half in stages 1 and 2; SCBIV = equal to SCBIII + addition of stage 3: recovery of used wood for new uses (BBP) and bioenergy (BIO).

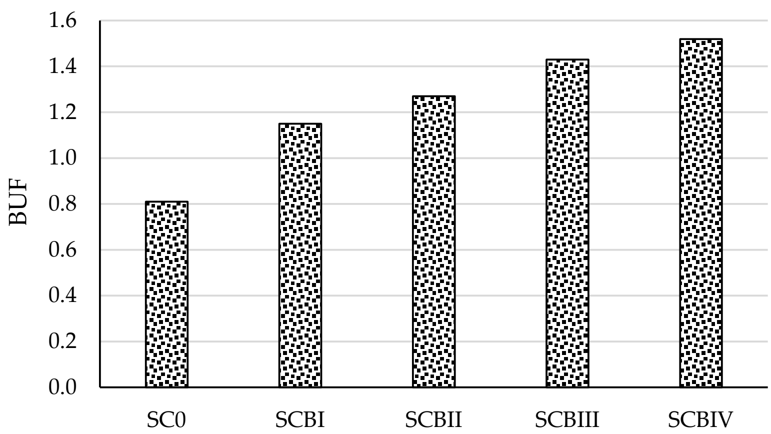

Figure 6. Evaluation of the application of different policies to the baseline scenario (SC0) using the BUF (Biomass Utilization Efficiency) indicator. The scenarios SCBI, SCBII, SCBIII, and SCBIV are described in Tables 3 and A1.

On the other hand, it is interesting to consider that the introduction of a single variant in the baseline scenario, i.e., the promotion of bioenergy use, significantly changes the situation and improves the BUF by almost 30% in the SCBI (more details can be found in Table A2 of Appendix A). Of course, such change would require adequate political support and efficient control and monitoring mechanisms that make it possible to respect local sustainability criteria and, therefore, maintain natural capital and the valuable provision of ecosystem services. The priority should always be to increase the efficiency of raw material use and only allocate the residual fraction to bioenergy, and never the other way around [4,24,39].

In SCBII, where the only change introduced is an increase in efficiency (by 15%) in the use of raw materials in the first stage of wood industrialization (higher BBP), the final BUF value is 1.27. The portion of raw material used increases from 43.7% to 58.7%. For the SCBIII scenario, where the only new variant is a reduction in the NUF fraction by half in both stages of the process (remaining at 10% in each case), the BUF reaches a value of 1.43. Finally, in the SCBIV scenario, all the previous improvements of the system are maintained and a new stage in the utilization cascade is added: 8% of the wood used in furniture or construction is recovered for other purposes, with 5% more waste for BIO.

This complementary proposal could represent a significant step forward in achieving a transparent numerical assessment aimed at evaluating the interconnections and reciprocal impacts of various policy measures among multiple sectors.

4.4. Biomass Use in the Forest Value Chain: Chemical Applications

As a final step in the analysis, it was interesting to estimate the residual biomass yield for some options that are currently relevant from the point of view of the chemical industry. Since we are dealing with lignocellulosic materials, a few products that could be obtained from the three main components of this biomass (cellulose, hemicellulose, and lignin) were selected. Appendix B summarizes the bioproducts studied, and the typical conversion routes to obtain them. Considering the theoretical data provided and referenced in [29], the yield of each BUE component for the selected products was plotted and is also shown in Appendix B. These products are BTL (biomass to liquid) as synfuel; furfural (from hemicellulose) and lactic acid (from cellulose); for category (ii): vanillin (from lignin); and for category (iii): biomethane, cellulosic bioethanol, and biodiesel. The average HHV (higher heating value) used for the industrial biomass categories was 16.85 GJ/t. The HHV considered for each type of bioproduct is shown in Appendix B, Table A3. Based on the residual biomass calculated from previous stages, the resulting values of different indicators for the industrialization process are shown in Figure 7. The values of Qb/Qp (amount of residual biomass (t) needed to obtain one ton of product) were obtained from [29] and complementary literature.

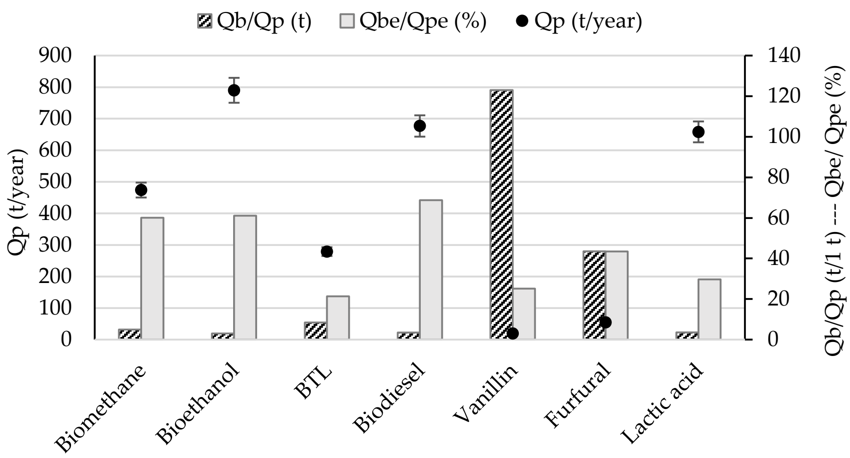

Figure 7. Biomass utilization efficiency (BUE) approach for the estimated RBτ at the industrial level. Where: Qp = product quantity (t/year) that could be obtained from the RBτ (±5%SE); Qb/Qp = amount of residual biomass (t) necessary to obtain one ton of product; and Qbe/Qpe = amount of biomass energy recovered in the bioproduct. It is assumed that only one type of product could be obtained at a time.

With the residual biomass available from the industrial level (2370 tDM/year), it would be possible to obtain about (Qp) 800 t per year of bioethanol, 700 t of biodiesel, or 20 t of vanillin per year, for example. This is only considering the chemical conversion that can be achieved with currently available technology in the selected conversion processes (Appendix B, Figure A1) and totally isolated from the socio-environmental life-cycle analysis of the forest chain. These estimates consider that all biomass is allocated to obtain one type of bioproduct at a time, since a series of reactions occurring simultaneously would be difficult to quantify with the proposed method. However, in modern biorefineries, multiple compounds can be extracted by optimizing reactions to harness various functional chemical groups.

Finally, with respect to Qbe/Qpe (amount of residual biomass energy recovered in one ton of bioproduct), the highest values are for biodiesel (68%), bioethanol (61%), and biomethane (60%). This implies that more energy will have to be invested than can be contained in these products. In other words, of the energy content available in the residual biomass, only a fraction can be recovered in the bioproduct depending on the type of product considered: in the worst case, less than 25% for vanillin. It is worth stressing that this basic analysis does not include any additional energy demand from the different stages (field, industrial, and commercialization) of the life cycle of the bioproduct (inputs, labor, fuels) in each context. Nor does it consider social and environmental impacts. It is merely an approximation based on the single chemical reaction defined. Furthermore, the BUE does not consider whether a process is exothermic or endothermic. This factor can significantly influence the ecological and economic sustainability of a process due to possible additional energy requirements for the chemical reaction and subsequent processing steps [28,29].

The value of bioproducts is highly dependent on the volume in which they are produced. Going forward, the trade-off between profit margins and production volumes should be weighted based on a market analysis that considers the technical feasibility of manufacturing the product and the identification of commercial partners to secure the value chain. This, of course, should be undertaken on top of a broad discussion of how to manage the ecological basis that will sustain such production [17,18,25].

4.5. Sustainable Forest Management and Circular Bioeconomy

Forest biomass value chains have been heavily criticized in recent decades, associating the use of woody biomass for energy with over-exploitation of forests, including permanent deforestation and tree burning [21,57], which run contrary to global goals regarding climate change, sustainable development, and biodiversity conservation. However, the greatest impacts on ecosystems would probably come from excessive land-use change that lacks planning and environmental assessments [32].

Likewise, for forest bioenergy to be an integral part of the forest sector, value chains must be planned through the design of integrated forest management approaches and considering national and regional specificities (forest policies, conversion technologies, forest management systems on the ground, logistics and markets, local productive capacity, biodiversity, etc.) [10,58]. The promotion of a circular forest-based bioeconomy implies that the forest biomass feedstock is the center of the system and must be carefully managed within a territorial planning scheme of multiple simultaneous objectives, where the natural value of the forest must be intrinsically recognized [17,59]. An in-depth understanding of the ecological basis that supports the entire forest chain and its potential response to different management systems and intensities of management is key to ensuring sustainable systems. This implies not only a continuous supply in terms of quantity, but also in terms of the quality of ecosystem services, particularly when dealing with highly valuable, multi-diverse native forests [59]. For example, since trees absorb CO_2 from the atmosphere during photosynthesis, woody biomass from sustainably managed forests can be used to generate bioenergy or other products that can be substitutes for non-renewable energy carriers or materials. Through this substitution, emissions associated with non-renewable energy sources or non-renewable materials will be avoided, simultaneously contributing to mitigating global climate impacts [53,58].

The circular bioeconomy approach requires, on the other hand, incorporating cascading use as one of the main axes around which proposals should be built. It consists of using resources such as wood or biomass over long periods and in different ways, mainly for material purposes, and reserving energy extraction for the final stages of the product life cycle [22–25,60]. Although undoubtedly there is still much to debate about this model, which appears as an alternative, for it to truly be one [61,62], the possibility of introducing circular bioeconomy principles (minimization of material use, waste reduction, reuse, recycling, etc.) within a cascading scheme requires the study of each forest system, considering the value chain in its entirety. The forest biomass that could be reinserted in new harvesting routes is subject to numerous restriction criteria, first considering that the prioritization should be given to the most efficient and planned use of forest raw material, thereby reducing the amount of residual biomass, and not the other way around [3,4]. This requires management plans based on ecological studies and not just on regulatory limits, which in many cases do not consider the diverse life strategies of trees and the delicate balance they maintain [63]. In a context of traditional use of native forests without planning, where their importance has been underestimated, and where they are still subject to threats from deforestation and degradation, the reckless promotion of energy use could ensure their extinction without the expected benefits [31]. In countries with lax enforcement of forest laws, the responsible procurement of wood resources emerges as a crucial consideration [3,21,24].

5. Conclusions

The methodological proposal presented here allows us to account for key technical aspects that are needed to advance the development of circular forest bioeconomies, as well as to highlight underlying issues that should be explored in the future and analyzed in a complementary manner. The case study shows that the productive and sustainable use of forest biomass has important limitations that must be considered. In fact, the maximum or theoretical potential is rapidly reduced with the inclusion of only a few technical and technological constraints.

In particular, the possibility of using native forest field biomass requires not only the generation of specific information at the plot level, but also the adoption of ecology-based forest management plans. Beyond identifying opportunities for rural bioenergy, planning the management and use of biomass from native forests and their respective industries is essential to ensure a constant and reliable supply of raw materials over time, and to thereby obtain the expected benefits. Dialogue and the search for consensus are essential to achieve the desired sustainability through the implementation of bio-based, comprehensively planned, and participatorily designed strategies. The fact that native forest biomass availability is highly dependent on the characteristics of the socio-economic systems where it grows or is generated (silvicultural practices, management systems, cultural value, etc.) is a major challenge for sustainable forest management and the fulfilment of circular bioeconomy principles.

Small rural economies still have a long way to go to achieve small bio-based businesses (including small biorefineries) with cascade use schemes that are territorially appropriate, as they must first address basic structural barriers (unsatisfied basic needs, health, labor and hygiene aspects, political or regulatory barriers, etc.). However, planned energy use constitutes a practical and concrete alternative today. This work provides important tools to accelerate this necessary ecological and energy transition.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en16207140/s1. Table S1: international standards for the study and characterization of solid biofuels.

Author Contributions: Conceptualization, S.M.M.; methodology, S.M.M.; validation, R.J.T. and Q.R.Q.B.; formal analysis, S.M.M., R.J.T. and Q.R.Q.B.; investigation and data acquisition, S.M.M., C.R.S. and M.A.T.; resources, M.A.T. and S.M.M.; data curation, M.A.T. and S.M.M.; writing—original draft preparation, S.M.M.; visualization, S.M.M.; writing—review and editing, Q.R.Q.B. and R.J.T.; supervision, S.M.M.; project administration, S.M.M.; funding acquisition, S.M.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Description of Scenarios

Table A1. Scenarios considered for the circularity analysis of the biomass of the forestry chain under study. Where: SC0 = baseline scenario; and alternative scenarios: SCBI to SCIV. For more detail on the values assumed for each scenario, see Table 3.

Scenario	Description and Assumptions
Current (SC0)	The industrial sector of wood in the province of Jujuy comprises two well-differentiated subsectors: (i) primary industrialization that processes the log and obtains the sawn wood and (ii) secondary industrialization that processes the log or directly the sawn wood for the production of packaging wood, openings, furniture and other carpentry products [15,16]. The raw material that enters the industrial process is BBP. There is very low transformation efficiency in the use of raw material. Old technology and in many cases, manual [12,49]. There is no energy use of biomass (BIO). If there is, it is isolated, reduced and not quantified. Only on certain occasions, the shorelines or solid remains are used for firewood, which is sold or given away. The BBP fraction that is considered at the beginning of stage 2 is only the one that is assumed to have been able to be transformed into new products. The forest residues generated in the value chains that have some alternative use are sawdust, which is sold or exchanged for bricks to those who manufacture it. Sawmills express concern that the sector has regarding the future availability of native wood logs [16]. This fraction is included within UF, and therefore assumes a recovery value of 10% of by-products between stages 1 and 2 (UF). Finally, a very high material loss fraction is considered, not returned to the atmosphere (NUF). More detail on the baseline scenario can be seen in Section 4.3.
Change	
	The policy is introduced: regulation of logistics, commercialization, and use of residual biomass for energy purposes. Result: the scenarios from now on include bioenergy use (BIO), since this use is included in the forestry chain.
SCBI	The same as SC0 but with the use of bioenergy. Hypothesis: A raw material management policy is introduced that prohibits its uncontrolled burning or its disposal without it having entered a new stage of use in a circular scheme. Result: the unused fraction (NUF) is reduced by 31% and 5% (stage 1 and stage 2, respectively). A loss of 20% remains.
SCBII	Same as SCBI plus a 15% efficiency improvement (BBP fraction) in stage 1. Hypothesis: a technology park renewal policy and cooperative organization of activity are introduced. Result: efficiency is improved in the first stage of the forestry chain and the raw material is better used, reducing waste.
SCBIII	Same as SCBII plus a halving of NUF in stage 1 and 2. Hypothesis: a training policy is introduced in management of the use of raw materials and by-products. Result: in addition to the previous one, the reduction of waste (NUF) by use (bioenergy) is achieved in both stages of the chain.
SCBIV	Same as SCBIII plus the addition of stage 3: recovery of wood for other uses and bioenergy. Hypothesis: a policy is introduced that defines a comprehensive solid waste management plan, with planning at the territorial level. Result: a new stage is added in the cascade scheme of the chain, where there is recovery of already used wood, in addition to the use of bioenergy.

Table A2. Evaluation of the application of different policies to the baseline scenario.

Scenario	BI	PE	BUF Partial	BUF Final
SC0	1 0.436	0.486 0.75	0.486	 **0.81**
SCBI	1 0.436	0.8 0.8	0.8	 **1.15**
SCBII	1 0.587	0.8 0.8	0.8	 **1.27**
SCBIII	1 0.587	0.9 0.9	0.9	 **1.43**
SCBIV	0.7	0.13		**1.519**

Where: SC0 = no use of bioenergy. Recovery of 10% of by-products between stages 1 and 2 (UF). SCBI = same as SC0 but with the use of bioenergy. SCBII = same as SCBI + 15% efficiency improvement in stage 1. SCBIII = same as SCBII + NUF reduction by half stage 1 and 2. SCBIV = same as SCBIII + addition of stage 3: recovery of wood for other uses and bioenergy.

Appendix B. Details of the BUE Method

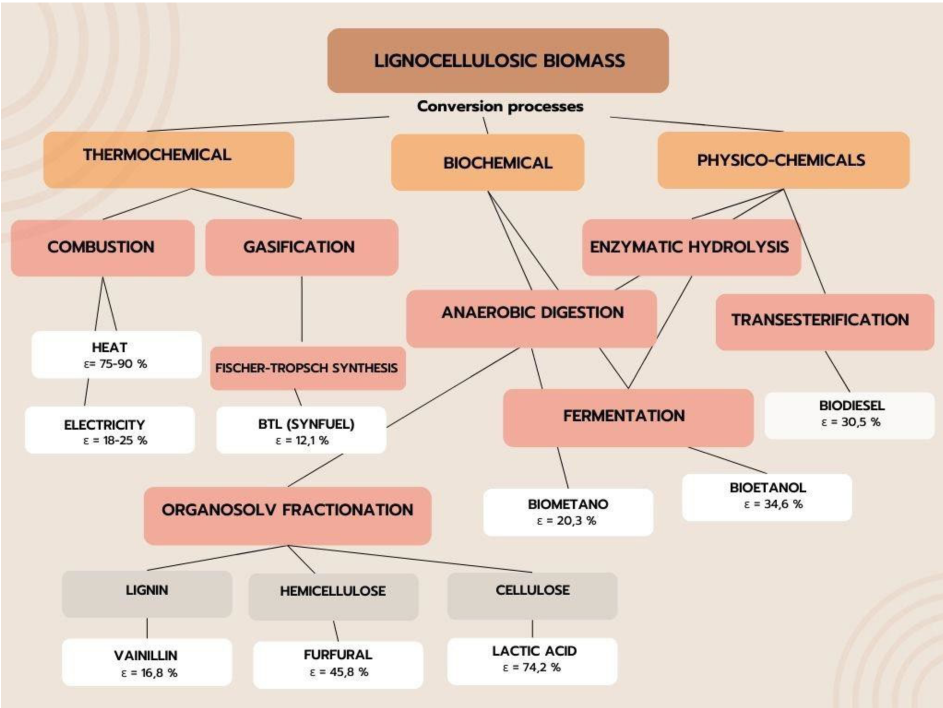

Figure A1. Representation of the conversion routes used from lignocellulosic biomass and the most frequent bioprocesses, to obtain the seven bioproducts that were considered in the paper: BTL (biomass to liquid) as synfuel; furfural, lactic acid, vanillin, biomethane, cellulosic bioethanol and biodiesel. Where E = possible technological efficiency currently used for the calculations, which corresponds to the value of BUE_H reported in Table A3. Own elaboration.

The conversion pathways addressed shown in Figure A1 are: (a) thermochemical; (b) biochemical and (c) physicochemical.

Within the first, the two most used processes were considered: combustion and gasification. The first produces heat and/or electricity. Their analysis was included in the determination of BioTP and BioTA. Gasification, on the other hand, produces a gas that can be subjected to other processes (such as the Fischer Tropsch synthesis) that can result in synthetic liquid biofuels (biomass to liquid process, BTL), with high value for use in the automotive industry or for its employment in the chemical industry.

In the second route, two energy conversion processes have also been considered: anaerobic digestion, to obtain biomethane; and fermentation, to obtain cellulosic bioethanol for the automotive sector as a product.

Finally, in the physicochemical route, three processes have been considered: transesterification (to obtain biodiesel); enzymatic hydrolysis and then fermentation (to obtain cellulosic bioethanol) and finally, the organosolv fractionation process, which makes it possible to treat lignocellulosic waste to separately obtain its three main components: high-quality cellulose, hemicellulose and lignin (see further details of the process in [64]). For each of these three fractions, lactic acid, furfural and vanillin have been considered as a bioproduct for analysis, respectively (Figure A1).

In the case of BUEs, stoichiometric or theoretical BUE, outlines the proportion of biomass feedstock that ultimately becomes part of the final product solely based on the inherent chemical reaction. However, in practice, with the available technological efficiencies and acceptable costs to carry out these bioprocesses, the maximum BUE_H is notably lower (Table A3). These data are founded on information accessible in the public domain from literature up to April 2015, along with insights obtained from discussions with professionals in the industry [29]. These efficiencies typically involve finding a balance between the expenses associated with processing and the rate of processing (throughput).

Table A3. Comparison of the performance of the different bioproducts obtained from lignocellulosic biomass, for each of the BUE (biomass utilization efficiency) components. Own elaboration based on [29] and cited references.

	BUE_S (%)	E (%)	BUE_H (%)	HHVp (kJ/g)	BUE_E (%)
Biomethane	34.3	59 [65]	20.3	50	60.1
Bioethanol	56.8	61 [66–68]	34.6	29.7	61.1
BTL	34.6	35 [69]	12.1	49.5	21.3
Biodiesel	42.3	72 [70,71]	30.5	38	68.7
Vanillin	70.8	23 [72,73]	16.8	26	25.1
Furfural	60.4	75 [74,75]	45.8	16	43.4
Lactic acid	90	82 [76–78]	74.2	17.5	29.7

Where: BUE_S = BUE stoichiometric; BUE_H (high) = Bue realistic biomass (highest) that is likely to be incorporated into the final product based on actual yields for the described synthesis route (calculated as BUEs * E)/100); BUE_E = BUE energetic (it is the energy of the original biomass that remains in the product); E = technological efficiency with which the processes currently occur as reported in the literature and expert opinion (%); HHVp = higher heating value of the bioproduct. The HHV of the biomass considered for the analyses is 16.85 kJ/g.

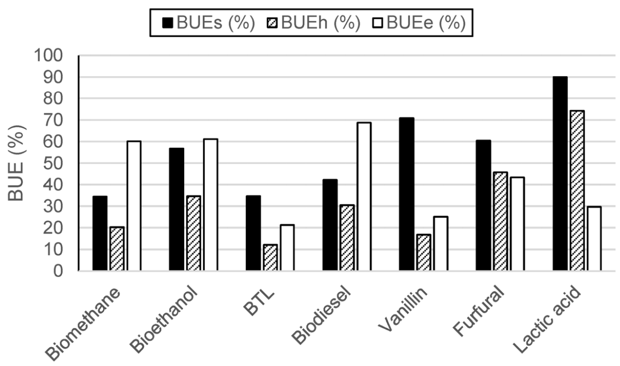

Figure A2. BUE approach for RBτ of industrial level available in the case study (Caimancito forest basin, Argentina). Where: BUE = Biomass Utilization Efficiency for 7 processes and products: chemicals, polymers and fuels (from industrial biomass feedstocks estimates). BUE_S = BUE stoichiometric; BUE_H = Bue realistic biomass (highest); BUE_E = BUE energetic. Own elaboration based on [29], cited references and own data.

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