Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-024-05673-4

CORRECTION

Correction to: Biomass and bioenergy potentials of bioresidues: assessment methodology development and application to the region of Lafões

Ana d'Espiney[1,2,3] · Helena M. Pinheiro[4] · Isabel P. Marques[1] · Jörg Kretzschmar[3] · Karl-Friedrich Cyffka[2] · Daniela Thrän[2,5,6]

Correction to: Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-023-05168-8

In the original published paper the value of biomass potential for one of the residues (sewage sludge) is mistakenly presented as 1000-fold higher than the correct value. This mistake does not affect the proposed methodology and its application, but changes the results of the case study and, consequently, its discussion. Therefore, the results tables (Tables 3 and 4) with the corrected values are here submitted, together with the revised text in the Results, Discussion and Conclusions sections.

1 Results

The results of the biomass potential assessment at the different levels (theoretical, technical, used and mobilizable) are presented in Table 3. Together, the four categories produce 107,431 t DM year^{-1} of biomass, theoretically. Since 3917 t DM year^{-1} is not accessible, it results in a technical biomass potential of 103,513 t DM year^{-1}. Of these, 1752 t DM year^{-1} are already in use, meaning that 101,762 t DM year^{-1} are mobilizable for bioenergy purposes.

The category of agricultural by-products produces the second highest biomass amount, most of it from livestock production, one of its two subcategories. The other, biomass from orchards, groves, and vineyards pruning, presents a biomass potential two orders of magnitude lower. Moreover, it is a used technical potential, resulting in a neglectable contribution to the biomass potential of the overall category. The mobilizable biomass potential of this category is therefore that of its sub-category livestock, 41,339 t DM year^{-1}. The category of forestry residues shows the highest technical biomass potential of 60,302 t DM year^{-1} (65% from eucalyptus and 35% from maritime pine), all of it mobilizable. The category with the lowest technical biomass potential is municipal waste with 1751 t DM year^{-1} (54%, 39%, and 7% from biodegradable waste, green waste, and sewage sludge, respectively), almost all not mobilizable since only the one with the lowest biomass potential, sewage sludge, is mobilizable.

The top three residues in terms of biomass provision, representing 94% of the total mobilizable biomass potential of

---

The original article can be found online at https://doi.org/10.1007/s13399-023-05168-8

✉ Ana d'Espiney
ana.despiney@tecnico.ulisboa.pt

[1] Bioenergy and Biorefineries Unit, LNEG – National Laboratory of Energy and Geology, Estrada Do Paço Do Lumiar, 22, 1649-038 Lisbon, Portugal

[2] Bioenergy System Department, Deutsches Biomasseforschungszentrum GmbH, Torgauer Strasse 116, 04347 Leipzig, Germany

[3] Biochemical Conversion Department, Deutsches Biomasseforschungszentrum GmbH, Torgauer Strasse 116, 04347 Leipzig, Germany

[4] Department of Bioengineering, iBB—Institute for Bioengineering and Biosciences, Associate Laboratory i4HB—Institute for Health and Bioeconomy, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

[5] Department of Bioenergy, Helmholz Center for Environmental Research, Torgauer Strasse 116, 04247 Leipzig, Germany

[6] Chair of Bioenergy System, Faculty of Economic Sciences, University of Leipzig, Grimmaische Straße 12, 04109 Leipzig, Germany

Table 3 Theoretical, technical, used, and mobilizable biomass potentials of the residues of Lafões

Residue	Biomass potential level			
	Theoretical (t DM yr^{-1})	Technical (t DM yr^{-1})	Used (t DM yr^{-1})	Mobilizable (t DM yr^{-1})
Woody biomass from apple orchard	62	12	12	0
Woody biomass from olive grove	208	42	42	0
Woody biomass from blueberry orchard	125	25	25	0
Woody biomass from vineyard	136	68	68	0
Cattle manure	6608	5344	0	5344
Pig manure	267	267	0	267
Poultry manure	36,176	35,729	0	35,729
Total agriculture by-products	*43,581*	*41,486*	*147*	*41,339*
Eucalyptus forestry residues	40,084	39,335	0	39,335
Maritime pine forestry residues	22,014	20,967	0	20,967
Total forestry residues	*62,098*	*60,302*	*0*	*60,302*
Biodegradable waste	942	926	926	0
Green waste	689	679	679	0
Sewage sludge	120	120	0	120
Total municipal waste	*1751*	*1725*	*1605*	*120*
Total Lafões	*107,431*	*103,513*	*1752*	*101,762*

Italicized values represent sum total results by category and for the entire region

DM dry matter

Table 4 Theoretical (Theor) and technical (Tech) bioenergy potential of the residues of Lafões through conversion by anaerobic digestion, combustion, gasification, and pyrolysis

Residue	Technology							
	Anaerobic digestion (TJ yr^{-1})		Combustion (TJ yr^{-1})		Gasification (TJ yr^{-1})		Pyrolysis (TJ yr^{-1})	
	Theor	Tech	Theor	Tech	Theor	Tech	Theor	Tech
Apple woody	ns	ns	0.2	0.1	0.1	0.1	na	0.1
Olive woody	ns	ns	0.7	0.2	0.5	0.3	na	0.3
Blueberry woody	ns	ns	0.4	0.1	0.3	0.2	na	0.2
Vineyard woody	ns	ns	1.2	0.3	0.6	0.3	na	0.5
Cattle manure	38.0	21.5	ns	ns	ns	ns	ns	ns
Pig manure	1.9	1.1	ns	ns	ns	ns	ns	ns
Poultry manure	264.5	154.0	ns	ns	ns	ns	ns	ns
Total agriculture by-products	*304.3*	*176.6*	*2.5*	*0.6*	*1.5*	*0.8*	*na*	*1.1*
Eucalyptus forestry	ns	ns	590.0	147.5	445.8	245.2	na	344.1
Maritime pine forestry	ns	ns	356.4	89.1	238.8	131.4	na	193.7
Total forestry residues	*ns*	*ns*	*946.5*	*236.6*	*684.6*	*376.5*	*na*	*537.8*
Biodegradable waste	6.2	3.3	ns	ns	ns	ns	ns	ns
Green waste	6.7	4.5	8.0	2.0	na	3.7	na	4.1
Sewage sludge	1.0	0.6	ns	ns	ns	ns	ns	ns
Total municipal waste	*14*	*8*	*8.0*	*2.0*	*ns/na*	*3.7*	*ns/na*	*4.1*
Total Lafões	*318*	*185*	*957.0*	*239.2*	*686.1*	*381.1*	*0.0*	*543.0*

Italicized values represent sum total results by category and for the entire region

ns not suitable, *na* not assessed

Lafões, are maritime pine forestry residues (21%), poultry manure (35%), and eucalyptus forestry residues (39%).

The results of the subsequent bioenergy potential assessment are presented in Table 4. A theoretical bioenergy potential of 318 TJ year^{-1} was obtained for biochemical conversion, 42% being consumed in process operations, resulting in a technical bioenergy potential of 185 TJ year^{-1}. Among thermochemical conversion options, combustion gives the highest theoretical bioenergy potential, but due to higher losses in process operations ends up providing the least energy, with a technical potential of 239 TJ year^{-1}. Gasification shows the second highest technical bioenergy potential, 381 TJ year^{-1}, only exceeded by the technical potential of 543 TJ year^{-1} from pyrolysis.

Nevertheless, according to the biomass cascading use principle, when assessing residues with high lignin content the biorefinery technologies should be considered, namely, the production of bioadsorbents [16]. This means that the bioenergy technical potential values for combustion and gasification in the region of Lafões should rather be represented with the ranges 3–239 TJ year^{-1} and 5–381TJ year^{-1}, respectively, where the lower end value of the range respects the cascading principle. In this same line of reasoning, it is better to represent the bioenergy theoretical potential with the ranges 11–957 TJ year^{-1} and 2–686 TJ year^{-1} for combustion and gasification, respectively.

According to the present methodology, when energy conversion factors are not available and gas or bio-oil yields associated with a given energy production facility are considered (which was the method selected for pyrolysis), the technical energy potential is being assessed and therefore is not possible to present a result for the theoretical bioenergy potential for pyrolysis, so this option was not used for comparison purposes.

Adding up the best results for the two conversion routes, namely anaerobic digestion and pyrolysis, the technical bioenergy potential of the residues of Lafões is 724 TJ year^{-1}, 26% of it from anaerobic digestion. The category of agriculture by-products contributes 25%, with a technical potential of 178 TJ year^{-1} (177 TJ from anaerobic digestion of livestock manure and 1 TJ from pyrolysis of biomass from pruning). The category of forestry residues shows a technical bioenergy potential of 538 TJ year^{-1} (74% of the total) from pyrolysis of the two residues included in it (344 of which are from eucalyptus). At the bottom is the category of municipal waste, with a technical bioenergy potential of 8 TJ year^{-1} (2% of the total), mainly from anaerobic digestion of biodegradable and green waste (3.3 and 4.5 TJ year^{-1}, respectively).

In terms of the top individual residues for bioenergy provision in the Lafões region, again three of them represent 96% of the total technical energy potential but following a distribution other than that for biomass potential. Specifically, poultry manure has the lowest contribution (12%), followed by maritime pine (27%) and eucalyptus (48%) forestry residues.

2 Discussion

The presented results show that Lafões can recover more energy from its bioresidues through the thermochemical conversion options, when compared with the biochemical route. The region is characterized by high values of biomass and bioenergy potentials from livestock farming, more suitable for the biochemical route, and from forestry residues, more suitable for the thermochemical route. Taking only the top three residues (poultry manure and pine and eucalyptus forest residues), anaerobic digestion of poultry manure can provide 154 TJ year^{-1} against 538 TJ year^{-1} achieved with the pyrolysis of forest residues.

The residue materials other than the top three can still deliver up to 32 TJ year^{-1}. Of this, only 9 TJ year^{-1} are already in use, through composting of woody agriculture by-products and processing of municipal biodegradable waste and green waste outside Lafões, so the remaining 23 TJ year^{-1} (from cattle and pig manure and sewage sludge) should be included in design scenarios for integrated energy systems. For example, there are poultry production facilities nearby cattle production facilities, and, since there are no significant changes in feedstock collection costs, anaerobic co-digestion of the two manures is a reasonable option. Moreover, it can reduce microbial inhibition issues from the low C:N ratio value of poultry manure (around 8), since cow manure has a typical C:N ratio of 18 [44].

It is uncertain how much of the regional energy demand can be covered by the assessed residue energy potential, since publicly available data on total energy demand are not discretized by municipality. The INE indicates a value of 406 TJ only for electrical energy demand in the three Lafões municipalities in 2020 [32]. The calculated residue yearly potential of 724 TJ thus represents 178% of this electrical energy consumption. If it could ultimately be converted using CHP processes with an electrical yield of 40%, 71% of the 2020 electrical energy demand could be covered. Given the strong presence of manufacturing industries in Lafões, heat is expected to be an energy vector under high demand, but an assessment of the industrial energy needs, and the features of the production processes (e.g., their temperature ranges) is necessary for deciding the best allocation of resources.

The methodology as applied in the present assessment has limitations that should be highlighted. First, complete availability of the mobilizable potential for energy purposes is assumed, neglecting the growth of non-energy biomass demand and thus resulting in an overestimated bioenergy potential. Second, although the methodology foresees the improvement of assessments by including the energy demand of the conversion processes, not always considered in published reports, it is defined for this case study that burdens with feedstock provision are allocated to waste management, thus neglecting feedstock collection costs (energetic, economic, and environmental) for both conversion routes. It is therefore only possible to estimate the increase in energy production when compared to that of the current waste management practice in the region.

A detailed comparison between conversion route technologies and the prioritizing of actions is premature. To do such comparison, the cost of feedstock collection for each route should be computed in, which implies considering the context-specific exploitation characteristics of the feedstock in the region. One of these characteristics is an irregular topography associated with a smallholding character in forest production and exploitation, dictating a dispersed location and ownership of the production of feedstocks suitable for the thermochemical conversion route. Part of the feedstock production for the biochemical conversion route is also somewhat dispersed, due to a significant presence of small-scale poultry production units. These constitute a barrier for the development of bioenergy systems. Medium- to large-scale production facilities are also represented, but their weight in the region still remains to be assessed. The other feedstock suitable for biochemical conversion, sewage sludge, comes from more centralized facilities.

There are benefits in economic performance associated with large-scale power plants, which are difficult to obtain due to the dispersed and small-scale ownership of forestry residues [45]. In addition, the entities that are presently in charge of the disposal of forestry residues mainly have no commercial exploitation in view and hardly any investment capacity. This means that regardless of its expectable economic performance, is it not possible to implement the thermochemical route unless other economic agents take over or intervene.

The expectations laid on bioenergy to confer more flexibility to the regional energy mix, filling in the gaps of the intermittent wind-based electricity generation, should also be considered in identifying the residue/technology that demands priority action. The provision of flexibility services in short and medium term implies investments in CHP units. This is an obstacle in the thermochemical conversion route, due to the aforementioned limited investment capacity of the region's forestry sector. The fulfilment of long-term flexibility services implies the upgrading of fuels, e.g., biogas to biomethane, gas from gasification to biobased synthetic natural gas or the bio-oil from pyrolysis. This requires investments that only the large-scale economic agents dealing with poultry manure can secure.

In terms of energy vectors, a high demand for heat is expectable in the region, and thus the bio-oil from pyrolysis can lose priority. This leaves the other two less efficient options of thermochemical conversion, both with better energetic performances than the biochemical conversion route. Nevertheless, the latter appears to benefit from regional-specific characteristics, such as feedstock distribution and collection and placement of investment capacity, as well as the ability to meet regional energy vector needs.

Therefore, any improvement of the environmental and economic performances, to be achieved through the implementation of bioenergy technologies, seems to be possible only through the biochemical conversion route, since it assumes the additional role as "anchor and/or upcycling tenant" by supplying agriculture fertilizer, replacing chemical fertilizers, and optimizing the environmental performance [46], thus respecting the biomass cascading use principle. Although pyrolysis-producing biochar also improves the environmental performance [16], the financial barriers to the implementation of the thermochemical conversion route, mentioned above, render this technology unattainable.

But more barriers can be foreseen for the mobilization of the bioenergy potential in the region. The above-mentioned use of its co-products, such as the organic fertilizer, faces challenges not only in terms of transport, handling, storage, and field applications, but also in terms of their market acceptance due to a negative public perception of digestates [46]. In what concerns the implementation itself of bioenergy systems, legislative, financial, research, teamwork, local support, and personnel training barriers can be predicted [47], some being already experienced in the region. The postponing of the Biomethane Action Plan under REPowerEU is one example.

One of these barriers was experienced within the present assessment, namely the hesitation to provide information on feedstock availability (described as a local support barrier [47]). Achieving optimal potential for this role requires the assessment of all available feedstocks, namely considering the industrial residues category. The characteristics of the latter and their current disposal practices can point to new priorities and the investment capacity of the economic agents associated with them can also influence decisions.

When planning the next steps to mobilize the assessed potentials, more information on the environmental and economic performances of the conversion routes is necessary. For example, avoiding emissions caused by current context-specific feedstock management systems can cause action on a specific residue to become a priority, with the implementation of the associated specific route. That is the case of the present open-air burning of forestry residues, but can also apply to manure composting or the landfilling of sewage sludge.

Beyond action priorities, the ambitious goals of the RED II [48] and the current RED II revision proposal [49] by the European Commission (EC) require a massive mobilization of biogenic residues and feedstocks for the production of advanced biofuels, and thus all residues and conversion routes are a priority. The National Energy and Climate Plan (NECP) of Portugal (resolution of the Council of Ministers no. 53/2020 [50]) outlines the need for ca. 7 PJ of advanced biofuels in 2030, and the present assessment results show that roughly 18% of this requirement could be met with the 1 PJ year^{-1} produced from the residues of Lafões. The EC proposal points to even higher requirements of advanced biofuels and the analysis of the biomass potentials should therefore be extended to the entire territory in all member states.

Moreover, when pursuing circular economy and industrial symbiosis objectives, the co-processing of complementary substrate mixtures can be necessary, and here, there is a marked lack of knowledge on expectable yields and potentials. Mixtures of maritime-pine forestry residues with poultry manure have been shown, albeit at a very low Technology Readiness Level (TRL), to lead to improved performance of the biochemical conversion route [34, 51]. Sewage sludge with its high biomass potential is gaining visibility for the possible implementation of symbioses. Wastewater sludge treatment can be redesigned to enable the application of the digestion process to mixed feedstocks that are complementary in chemical composition but are hard to mix due to density differences. The yields and potentials of such symbiotic conversion routes remain largely unknown and the performance increment from the management of complementarities is presently disregarded. In any case (individual or symbiotic routes), the assessment of their performance should be made also through life cycle analyses (LCA) and life cycle costing (LCC).

3 Conclusion

The application of this multistep methodological assessment shows the possibility of fulfilling all electrical energy demands of the case-study region of Lafões with the energetic conversion of its bioresidues. However, the assessment of the role of this bioenergy in providing flexibility services to the regional heat and electrical power sectors must be performed. The potential utilization of the residues bioenergy in combination with other renewables or in applications which are difficult to defossilize must be weighed. An assessment of the energy performance of all options including LCA and LCC should be performed.

The assessment identified three top residues produced in Lafões, namely poultry manure and pine and eucalyptus forestry residues. The biochemical conversion route, anaerobic digestion, leads to the worst energy performance, but with indications that it will provide better environmental and economic performances than the thermochemical options. The feedstocks suitable for biochemical conversion, poultry manure, can benefit from economies of scale due to the operation of large-scale facilities in the region. Nevertheless, the production of woody industrial residues in the region is non-negligible, and further assessment of the industrial residues category can lead to changes in the prioritization of conversion routes.

Beyond the scope of the present assessment, the development of complete and updateable resource databases, using the potential level-based methods outlined in the present methodology, should be carried out at countrywide or even wider levels, but still considering the regional contexts. Assessments are often focused solely on estimating theoretical or technical potentials, an insufficient approach for a future bioeconomy that increasingly requires the consideration of conflicting use interests. The present assessment improves on previous reports in considering the fractions already in use, such as biomass demand for non-energy (material) uses, aiming to assess the mobilizable energy potential, but there is still room for broadening its scope.

Bioenergy research is reporting needs to clarify yield definitions and provide more complete assessments of potentials. This is already the case of the bioenergy conversion routes assessed here, but it is especially important when new conversion routes are addressed, arising from the management of mixtures and their complementarities. The verification and benchmarking of results reported for experimental efforts, as well as their upscaling, recommends such clarification.

The original article has been corrected.