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Bioenergy Potential of Complementary Bio-Wastes from the Lafões Region: Poultry Industry and Forestry

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In order to optimize bio-waste management in the region of Lafões (Portugal), comprising a large production of forestry and poultry production residues, complementarities were explored between the two bio-waste streams with respect to biogas production and energy recovery.

The forestry biomass potential was assessed through a methodology using Geographic Information System data together with technical, land use and accessibility information. The poultry biomass potential was estimated according to IPCC guidelines. The energy potential of these biomass sources was assessed through bench-scale anaerobic digestion assays with single and mixed substrates.

Conclusions are presented regarding the complementarity between these bio-wastes as bio-energy sources relevant for the Lafões region, showing increased energy potential through co-digestion.

1. Introduction

Decarbonization of human activities and promotion of a circular economy have dominated the debate in response to the climate and sustainability crisis. The transformation of waste management into resources management is mentioned in EU Directive 2018/851, as a strategy towards a circular and decarbonized economy. The recognition of waste as a valuable resource plays a central role in this response and inherent transformations.

This study was a challenge initiated by the Lafões Rural Development Association (ADRL), a forest management entity aiming to optimize bio-waste management in the region of Lafões (Portugal) in line with the forementioned EU Directive. Bio-waste mapping, although still ongoing for the different industrial sectors, has already indicated forestry and the poultry industry as potential suppliers of feedstocks for energy recovery. The values obtained in a first mapping effort were 67 Mt dry matter/year available from forest residues, mainly of the eucalyptus and pine classes (60% and 33% of the total, respectively), and 69 Mt volatile solids/year from poultry industry residues, mainly of the broiler class (78% of the total). These values prompted the present research aiming to explore complementarities between these two bio-waste streams, with respect to energy recovery by Anaerobic Digestion (AD).

Recovering energy from waste, besides avoiding the exploitation of non-renewable energy sources, can have a significant impact in the reduction of greenhouse gas emissions, since it avoids methane emissions to the air resulting from uncontrolled waste decomposition. Moreover, AD of organic waste can also significantly reduce the need for synthetic fertiliser production and the emissions associated with it. According to the World Biogas Association, emissions of 3,290 to 4,360 Mt CO_2 can be avoided through AD of wastes, representing 10 to 13 % of the global greenhouse gas emissions (Jain et al., 2019).

In the present study, the exploited scenario was therefore the conversion of the available organic waste into energy through AD. Complementarity between the two identified bio-waste classes was assessed through bench-scale tests of AD using single bio-waste substrate and co-digestion of mixed substrates (pine forest and broiler industry residues) under mesophilic conditions. The objective was to assess whether increased methane production could result from co-digestion, when compared to that achieved with single substrates, as recently reported in a literature review on the current status of anaerobic co-digestion (Karki et al., 2021).

The preliminary results were positive, highlighting the interest of further research into optimizing the complementarity between these substrates, and thus a second set of assays was performed, testing different proportions and classes within both bio-waste sources, the results of which are here reported.

The objective of this work is thus to provide insights regarding the potential for complementarity between the different types of identified bio-wastes. Considerations are given on the needs for further research on energy valorisation, combined with agricultural valorisation, of the different bio-waste types of the case-study region.

2. Methods and materials

The research here reported was conducted in two main steps, namely, feedstock mapping in the Lafões region and experimental determination of its biogas and bioenergy potential under different digestion and co-digestion scenarios.

To map the forest biomass, it was necessary to determine the effective area supplying biomass of each species, and this was done with geo-referenced data analysis through GIS-based methods, using ArcGIS version 10.5. That effective area takes into consideration technical restrictions to feedstock collection (Lourinho & Brito, 2015) and land use conflicts with nature conservation areas (Quinta-Nova et al., 2017). The forest roadmap was supplied by the competent departments in the three municipalities of the region of Lafões (Oliveira de Frades, São Pedro do Sul and Vouzela).

To obtain the forest biomass potential (FBP), the effective area was multiplied, as presented in Eq.(1), by the annual Residue Productivity (RP) and the percentage of the land covered by the Horizontal Projection of the Vegetation (HPV), as suggested in (Rocha et al., 2020).

$$FBP = A^{ef} \times RP \times HPV \qquad (1)$$

Where: FBP is the forest biomass potential supplied by the effective area of each class [t residue/(class.year)]; A^{ef} is the area for the supply of biomass of the forest class [ha]; RP is the fraction of residues of the forest class that can be effectively used for energy purposes [t residue/(ha.year)]; HPV is the percentage of land covered by the horizontal projection of the vegetation of the forest class [%].

For the mapping of the poultry industry residues, it was necessary to collect data on the number of birds bred in the industrial units of the region (registered and provided by the Directorate-General for Food and Veterinary of Viseu). The biomass potential for each poultry class (PBP) was calculated according to Eq. (2), that returns the amount of volatile solids excreted by each class of the poultry industry per year. The methodological assumptions and values for the parameters were those suggested by the IPCC guidelines (Dong et al., 2019).

$$PBP = \left[GE \times \left(1 - \frac{DE}{100}\right) + (UE \times GE)\right] \times \left[\frac{1-ASH}{18.45}\right] \times 365 \times number\ of\ birds \qquad (2)$$

Where: PBP is the poultry biomass potential of the region expressed as volatile solids excreted per poultry class [kg VS/(class.year)]; GE is the gross energy intake in the feed for an average bird of the poultry class [MJ/(bird.day)]; DE is the digestibility of the feed of the poultry class [%]; UE is the urinary energy expressed as mass fraction of GE; ASH is the ash content of manure calculated as mass fraction of the dry matter in the feed intake of the poultry class; 18.45 is the conversion factor for dietary GE per kg of feed dry matter [MJ/kg]; 365 is the number of days considered per year; the number of birds of the poultry class [bird/class] is also used.

The experimental determination of the bioenergy potential started with the selection of the bio-waste classes with higher energy potential, determined through Eq.(3) for the forest energy potential (FEP), with the Lower Heating Value (LHV) of each forest class presented in (Lourinho & Brito, 2015) and through Eq.(4) for the poultry energy potential (PEP), with the LHV of the methane presented in (Engineering ToolBox, 2003) and the methane production capacity (B_o) presented in (Dong et al., 2019).

$$FEP = FBP \times LHV \qquad (3)$$

Where: FEP is the forest class energy potential [GJ/(class.year)]; FBP is according to Eq.(1) [t residue/(class.year)]; LHV is the Lower Heating Value of the forest class [GJ/t residue @ STP].

$$PEP = PBP \times B_o \times LHV \qquad (4)$$

Where: PEP is the poultry energy potential of the poultry class [GJ/(class.year)]; PBP is according to Eq.(1) [kg VS/(class.year)]; B_o is the maximum methane production capacity of the manure of the poultry class [m^3 CH_4/kg VS]; LHV is the Lower Heating Value of the methane [GJ/m^3 CH_4 @ STP].

Samples from the selected bio-wastes were thus collected and transported to the laboratory within the same day. In the laboratory, all the samples were submitted to a pre-treatment (size-reduction and homogenization) and subsequently characterized by measuring bulk density, pH, solids and nitrogen contents according to Standard methods (APHA, 2012). Then, aqueous suspensions were prepared to measure the biogas production and bioenergy potential of different combinations of feedstocks and thus assess the complementarities between them. The employed 70-mL reactors were prepared in triplicate and operated in batch mode, under mesophilic conditions of temperature (37 ± 1 °C).

The following mother suspensions were prepared: four single-substrate runs, namely, chicken manure in straw litter (C), pine forest biomass (P), eucalyptus forest biomass (E) and Inoculum (I); and six mixed-substrate runs, specifically, chicken manure in straw litter with 30%, 50% and 70% of pine forest biomass (C+P30, C+P50, C+P70) and chicken manure in straw litter with 30%, 50% and 70% of eucalyptus forest biomass (C+E30, C+E50, C+E70). The composition of the feed to each reactor is presented in Table 1.

Table 1: Mother suspension composition | Substrates: straw litter chicken manure (CM), maritime pine residue (PR), eucalyptus residue (ER), wastewater from pavilion cleaning (WW), water (W) and inoculum (In)

Mother suspension	CM [mL]	PR [mL]	ER [mL]	WW [mL]	W [mL]	In [mL]	Total [mL]
Chicken manure in straw litter (C)	195.5			84.5		120	400
Pine forest biomass (P)		195.5			84.5	120	400
Eucalyptus forest biomass (E)			195.5		84.5	120	400
Chicken manure + 30% of pine (C+P30)	136.8	58.6		84.5		120	400
Chicken manure + 50% of pine (C+P50)	97.7	97.7		84.5		120	400
Chicken manure + 70% of pine (C+P70)	58.6	136.8		84.5		120	400
Chicken manure + 30% of eucalyptus (C+E30)	136.8		58.6	84.5		120	400
Chicken manure + 50% of eucalyptus (C+E50)	97.7		97.7	84.5		120	400
Chicken manure + 70% of eucalyptus (C+E70)	58.6		136.8	84.5		120	400
Inoculum (I)					280.0	120	400

As shown in Table 1, inoculum (collected from the sludge anaerobic digester of a domestic wastewater treatment plant) was added to all mother suspensions, at a concentration of 0.3 mL per mL of suspension. The preparation of these mother suspensions also incorporated the wastewater from cleaning of the poultry pavilion (WW). For this, a volumetric proportion between the liquid and solid substrates of 1:4.5 was used, the average value among those provided by several poultry production facilities in the region. The inoculum and the forest single-substrate runs were included in the study with the intention of measuring their individual biogas production potential (in the absence of CM).

The assay had a duration of 49 days and during this period biogas production was monitored regularly with a pressure transducer. Methane content in the biogas was monitored at the end, for the mother suspension C and for the assay that revealed the highest biogas production, by gas chromatography (the equipment used was the GC Thermo Electron Corporation Trace GC Ultra).

The relation between the mass of volatile solids in the CM feed to the reactor and the biogas production achieved thereof was calculated for all runs including CM, here called biogas production capacity (BPC). For the mother suspension C and that with the highest biogas production, the methane production capacity was calculated, and subsequently the associated energy potential (EP) for the yearly CM production of the most relevant poultry class of the region was estimated using Eq. (5).

$$EP = PBP \times \frac{Vol_{CH_4}}{VS_{CM} \times Vol_{CM} \times \rho_{CM}} \times LHV \qquad (5)$$

Where: EP is the energy potential of the CM in the mother suspension [GJ/(class.year)]; PBP is according to Eq.(1) [kg VS/(class.year)]; Vol_{CH_4} is the average accumulated methane production of the reactor [m^3 CH_4 @ STP]; VS_{CM} is the volatile solids content of the CM [Kg VS/g CM]; Vol_{CM} is the volume of CM added to the reactor [mL]; ρ_{CM} is the CM density [g CM/mL]; LHV is the Lower Heating Value of the methane [GJ/m^3 CH_4 @ STP].

3. Results

The results of the total FBP and the FEP estimated for the forest residues of the region are 67 Mt dry mass (DM) of residue/year and 1050 TJ/year, respectively, being presented in Table 2 for each forest class. The results of the total PBP and the PEP estimated for the poultry industry residues of the region are 69 Mt VS/year and 901 TJ/year, respectively, presented in Table 3 for each poultry class.

Table 2: Forest Biomass Potential (FBP) and Forest Energy Potential (FEP)

Forest class	FBP [DM t/year]	FEP [GJ/year]
Cork oak forest	1	20
Holm oak forest	2	33
Other oak forest	1447	21709
Chestnut forest	10	145
Eucalyptus forest	40084	601265
Invasive species forest	1106	15482
Other hardwood forest	2432	36484
Maritime pine forest	22014	374237
Other resinous forest	16	241

Table 3: Poultry Biomass Potential (PBP) and Poultry Energy Potential (PEP)

Poultry class	PBP [Mt VS/year]	PEP [GJ/year]
Broilers	54	696641
Laying hens	3	40667
Reproductive hens	7	92797
turkeys	5	70652

The results from the characterization of the bio-waste samples after pre-treatment are presented in Table 4.

Table 4: Sample characterization | Parameters: bulk density, total solids (TS), volatile solids (VS), nitrogen content (N) and pH. Values are expressed as average of duplicate analyses ± standard deviation.

Sample	Bulk Density [g/mL]	TS [g VS/g]	VS [g VS/g]	N [mg N/g]	pH
Chicken manure in straw litter (CM)	0.37 ± 0.11	0.7 ± 0.0	0.5 ± 0.0	25.1 ± 0.6	8.73
Maritime pine residue (PR)	0.30 ± 0.01	0.9 ± 0.0	0.9 ± 0.0	4.2 ± 0.8	4.40
Eucalyptus residue (ER)	0.30 ± 0.01	1.0 ± 0.0	0.9 ± 0.0	6.0 ± 0.6	4.71
Wastewater from pavilion cleaning (WW)	0.97 ± 0.02	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.6	6.94

The cumulative biogas production results, after the 49 days of the incubation period, are presented in Table 5, as well the biogas production capacity per volatile solids of CM added. The biogas production evolution along time is illustrated in Figure 1.

Table 5: Biogas production (BP), and average biogas production capacity (BPC) per unit VS of CM. BP values are expressed as average of triplicate runs ± standard deviation.

Mother suspension	BP [mL Biogas @STP]	BPC [m^3 Biogas/kg VS]
Chicken manure in straw litter (C)	146.4 ± 2.5	0.04
Pine forest biomass (P)	22.8 ± 0.2	Not applicable
Eucalyptus forest biomass (E)	13.5 ± 0.9	Not applicable
Chicken manure + 30% of pine (C+P30)	279.9 ± 19.0	0.10
Chicken manure + 50% of pine (C+P50)	171.5 ± 45.8	0.09
Chicken manure + 70% of pine (C+P70)	154.3 ± 10.3	0.13
Chicken manure + 30% of eucalyptus (C+E30)	127.0 ± 9.2	0.05
Chicken manure + 50% of eucalyptus (C+E50)	147.0 ± 10.4	0.07
Chicken manure + 70% of eucalyptus (C+E70)	74.9 ± 11.8	0.06
Inoculum (I)	3.1 ± 0.4	Not applicable

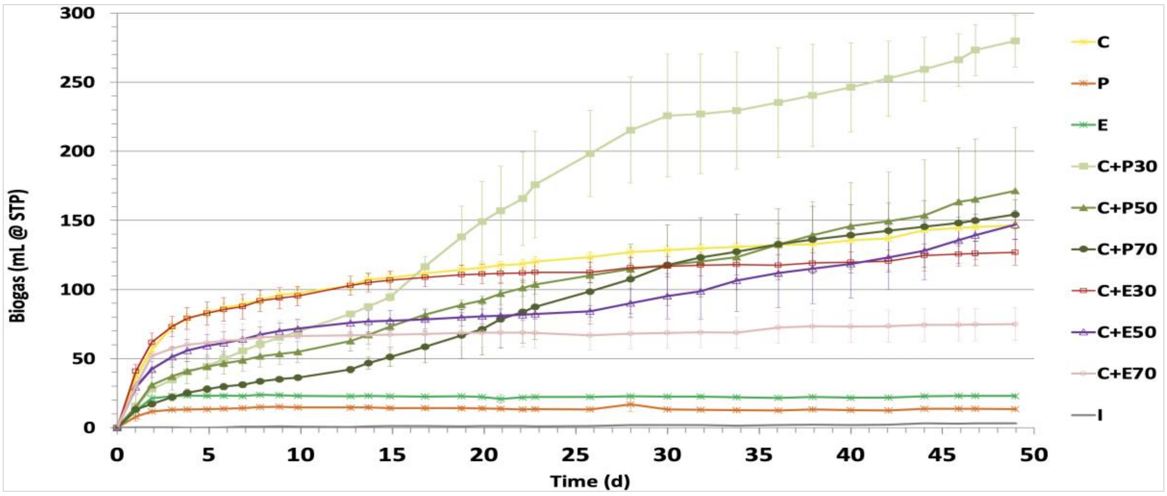

Figure 1: Time course of cumulative biogas production of the mother suspensions described in Table 1. Values are expressed as average of triplicate runs and standard deviation (error bars).

The methane volumetric content values in the biogas obtained for the mother suspensions C and C+P30, at day 46 of incubation, were 25.5 % and 53.1% (averages of the triplicate runs), respectively, which would result in an EP of 17.2 TJ/year and 103.4 TJ/year for the broiler class residues of the poultry industry of Lafões, respectively.

4. Discussion

The selection of the forest residue classes with higher potential energy value pointed to eucalyptus and maritime pine, since, as shown in Table 2, they present FEP values of 601 TJ/year and 374 TJ/year, respectively, which means that together they represent 92.9 % of the FEP of the region. Concerning the feedstocks from the poultry industry of the region, the broiler class was selected, since it presents an estimated PEP value of 697 TJ/year, as seen in Table 3, representing 77.3 % of the total PEP.

Observing Table 4, it is possible to see that the two forest samples have similar values of bulk density, total solids and volatile solids, but they differ in terms of their nitrogen contents, as well as pH. However, the latter differences are almost insignificant, when compared with that between them and the values obtained for the sample of chicken manure (CM). Since neutral pH and a high C:N ratio favour Anaerobic Digestion (AD), it was expected that both forest biomass residues would potentially promote biogas production, bringing about a decrease in the pH and an increase of the C:N ratio of the chicken manure when in admixture.

Nevertheless, as it can be seen in Table 5 and in Figure 1, only the mixed-feedstock AD runs to which pine residue (P) was added presented an increment of the biogas production, in comparison with singe-substrate runs. Irrespective of the percentage of P used, the cumulative biogas production was higher in the mixed-feedstock AD, when compared to the single-feedstock AD of the CM sample. The best results were achieved with the mother suspension identified as C+P30, with an increase in biogas production of 191 % when compared with the mother suspension C and of 178 % when compared with the average production of all the mother suspensions where CM was added.

Concerning the mixed-feedstock AD runs to which eucalyptus residue (ER) was added, none of the proportions showed a biogas production higher than that of the single-feedstock AD of the CM sample, with the 50 % eucalyptus forest feedstock (C+E50) reaching a comparable value only on the last day of incubation.

The behaviour of the biogas production of the different mother suspensions along the assay time also deserves attention, for the possible selection of the optimal incubation time. For the mixed-feedstock mother suspensions containing ER, the C+E30 and the C+E70 assays show no significant change in biogas production after the 13th day, but the C+E50 almost doubles its biogas production between the 25th and the last day measured. Regarding the mixed mother suspensions containing the PR sample, from the 16th day on the C+P30 mixture has a higher biogas production when compared with assay C, but for the other two PR proportions, only after the 36th day do they exceed assay C in biogas production. Therefore, it is advised to extend the incubation time and to observe the behaviour of forest residues containing runs thereafter.

Summing up, it can be proposed that the results obtained for the biogas production of the mixed-feedstock AD containing the PR and C samples, allow an optimistic perspective for the performance of this integrated solution, revealing complementarity between the two bio-wastes.

Also, regarding the methane potential, the results are promising, with a higher methane content in the biogas from the mixed-substrate AD, when compared with the single-substrate CM runs. The added pine residue produced a 6-fold increase in the methane production capacity of CM (mL CH_4/g VS), much higher than the 93.4% increase reported by (Karki et al., 2021) when CM was co-digested with wheat straw. Concerning the energy potential estimated for the broiler class of the region, 17.2 TJ/year when single-substrate digested and 103.4 TJ/year when co-digested with pine residues, it should be noted that it is advisable to perform assessments on further levels, namely in terms of the technical, economical, implementation and sustainable implementation energy potentials (Papilo et al., 2017). Also, the broader energy potential is yet to be determined, since some classes of both feedstock types that were left out of this preliminary study must also be taken into account in the calculation and tested in terms of their complementarity.

The large production of chicken manure in the Lafões region is presently handled through storage or pasture solutions, therefore emitting methane into the atmosphere. This represents a waste of its energy content and contributes to climate change. Further research is also needed concerning the biochemical mechanisms responsible for the increment in methane production when substrate complementarities in co-digestion are exploited.

5. Conclusions

The main conclusion that can be drawn from this case study is that integrated solutions, such as anaerobic co-digestion of complementary substrates, can be appealing from the point of view of their biogas and bioenergy potentials, as attested by the 6-fold increase in the methane production capacity of chicken manure when co-digested with pine forest residues.

The physicochemical composition of the different waste effluents generated by the industrial activities of the Lafões region should thus be analysed in more detail and their possible combinations experimentally assessed, in order to develop new pathways from bio-waste to energy.

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