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A. Zucaro, G. Fiorentino, G. Ansanelli

Abstract

Forestry residues and wood processing waste (residual biomass) represent the most challenging biowaste stream in the Pazardzhik Province (PP), Bulgaria, an area characterized by a strong forestry vocation. In the Business as Usual (BaU) scenario, 65% of forestry residues is valorized as pellets (60%) and compost (5%), while the remaining 35% is left in the forest. In the BBI-JI Biocircularcities project, two alternative scenarios were proposed in order to valorize the selected waste stream according to the principles of the circular bioeconomy and to address local stakeholders' concerns about frequent open forest fires. In detail, in both scenarios, an additional 25% of the forestry residues, unused in the BaU scenario, is valorized either energetically, in a Combined Heat and Power (CHP) plant (Bioenergy scenario) or through conversion into high value-added biochemical products (Biochemicals scenario). The alternative and BaU scenarios were evaluated and compared to each other from both environmental and economic perspectives, using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies, respectively. The results highlighted that the Biochemicals scenario is the most sustainable option, followed by the Bioenergy scenario.

Keywords: *LCA, LCC, Pazardzhik Province (Bulgaria), biochemicals, forestry residues, circular bioeconomy.*

Riassunto

I residui forestali e i rifiuti della lavorazione del legno (biomassa residuale) rappresentano il volume di rifiuti organici più consistente, nella provincia di Pazardzhik (PP), in Bulgaria, una zona caratterizzata da una forte vocazione forestale. Nello scenario Business as Usual (BaU), il 65% dei residui forestali viene valorizzato come pellet (60%) e compost (5%), mentre il restante 35% viene lasciato nella foresta. Nel progetto BBI-JI Biocircularcities, sono stati proposti due scenari alternativi per valorizzare i residui forestali e della lavorazione del legno secondo i principi della bioeconomia circolare e per rispondere alle preoccupazioni degli stakeholder locali riguardo ai frequenti incendi boschivi. In dettaglio, in entrambi gli scenari, un ulteriore 25% dei residui forestali, non utilizzato nello scenario BaU, viene valorizzato energeticamente in un impianto di cogenerazione (CHP) (scenario Bioenergia) oppure mediante conversione in prodotti biochimici ad alto valore aggiunto (scenario Biochimici). Gli scenari alternativi e il BaU sono stati valutati e confrontati fra loro sia dal punto di vista ambientale che economico, uti-lizzando le metodologie di Life Cycle Assessment (LCA) e Life Cycle Costing (LCC). I risultati hanno evidenziato che lo scenario Biochimici è l'opzione più sostenibile, seguito dallo scenario Bioenergia.

Parole chiave: LCA, LCC, Provincia di Pazardzhik (Bulgaria), prodotti biochimici, residui forestali, bioeconomia circolare.

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1. INTRODUCTION

The Biocircularcities (BCC) project, funded by the Bio-based Industries Joint Undertaking (JU) and the European Union's Horizon 2020 Framework Program through "Funding & tender opportunities" (BBI-2020-SO4-S4 Type of action BBI-CSA) champions the transition of urban areas towards a circular bioeconomy, focusing on optimizing biowaste management and promoting sustainable bio-based products. By analyzing three distinct pilot territories - the Metropolitan Area of Barcelona (Spain), the Metropolitan City of Naples (Italy) and the Province of Pazardzhik (Bulgaria) - BCC offers invaluable insights into biowaste valorization, circular economy practices, and the implementation of bio-based products.

Regarding the Pazardzhik Province (PP), given its strong forestry vocation, with 55% of the territory covered by forests, and the feedback from local stakeholders, engaged in the living labs organized by the BCC project in PP, forestry residues and wood processing waste (collectively referred to as residual biomass or biomass residues) were selected as the biowaste stream to be valorized according to the principles of circular economy.

In PP there is a mixed forest composed of 61% conifers (*Pinus sylvestris, Picea abies, Pinus nigra, Abies alba*) and 39% deciduous trees (e.g., *Quercus sp.*, *Fagus sp.*), with an average tree lifetime of 61 years. In 2019, the total 72,111 tons of forestry residues consisted of brushwood (3%), twigs (20%), wood lopping (41%), bark (20%), and stubs (16%) (Table 1).

Table 1 – Forestry residues produced in the PP pilot area (year 2018).

Forestry biowaste	Amount	Unit
Brush-wood (wetness is about 40-60%)	2,325	ton/yr
Twigs (50% wetness)	14,448	tons/yr
Wood loppings (55% wetness)	29,657	tons/yr
Bark (45% wetness)	14,550	tons/yr
Stubs (40-50% wetness)	11,131	tons/yr
Total	**72,111**	**tons/yr**

In the Business as Usual (BaU) scenario, most of forestry residues (65%) are processed into pellets (60%) and compost (5%). However, a significant amount (35%) is left on the ground, representing a problem for the local community. Indeed, accumulated forestry residues increase the risk of open fires, primarily caused by human activities to clear the forest floor (personal communication from the Regional Energy Agency of Pazardzhik, REAP). These fires can disrupt natural habitats, affecting the overall ecosystem, including pristine forests. Moreover, higher summer temperatures, due to climate change, further increase the risk of forest fires. In order to safeguard the forest ecosystem (Pergola et al., 2020; Titus et al., 2021; Pergola et al., 2022) and to address the related issues and challenges, as highlighted in the scientific literature, forestry residues must be managed carefully.

For these reasons, within the BCC project, two alternative scenarios, in line with the principles of the circular bioeconomy and the needs of local stakeholders, were proposed. In both scenarios, an additional 25% of forestry residues (gleaned from the unused residues) is valorized. Specifically, in the "Biochemicals" scenario, residues are used for biochemicals production (Ethyl levulinate-EL, 1,4-Butanediol – BDO, and Succinic acid- SA), through a biorefinery process.

In the second alternative scenario, namely "Bioenergy", forestry residues are processed into electricity and heat, in a Combined Heat and Power (CHP) plant, to replace the fossil counterparts. In detail, the electricity from the CHP plant increases the share of renewable energy in the national electricity mix, while the produced heat, used for self-consumption, replaces an equal amount of heat from fossil natural gas. The alternative scenarios were built considering the guidelines for sustainable forest management reviewed by Titus et al. (2021) and Pergola et al. (2020, 2022), which highlight that the amount of forest residues to be left on the soil should range from 10% to 30%, to maintain nutrient cycles and biodiversity. Conversely, excessive removal of carbon sources can lead to a long-term decrease in soil organic carbon, adversely impacting on the forest ecosystem.

Balancing the removal of forestry residues with sustainable forestry practices is challenging since it implies the development of cost-effective supply chains for collecting and processing these residues. Consequently, every proposal for the valorization of forestry residues, such as their conversion into energy or high value-added biochemical products, should always undergo a preliminary sustainability assessment. This assessment forms the basis for adopting good practices, implementing efficient and environmentally friendly technologies, and developing sustainable guidelines and policies for managing forestry residues.

In this study the environmental and economic performances of the three scenarios (BaU, Biochemicals, and Bioenergy) were evaluated through Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies.

A thorough assessment of the environmental and economic impacts of biowaste management is crucial in helping European cities achieve sustainable development by integrating environmental sustainability, economic growth, and welfare into decision-making processes.

2. LIFE CYCLE ASSESSMENT (LCA) OF THE FORESTRY RESIDUES MANAGEMENT SYSTEMS IN PP

In order to evaluate the environmental benefits and burdens associated to the residual biomass management in the investigated scenarios (BaU and two Alternatives, Biochemicals, and Bioenergy), a Life Cycle Assessment (LCA) study was performed.

The LCA was applied in compliance with the ISO Standards 14040 and 14044: 2006 (ISO 14040, 2006; ISO 14044, 2006) and ILCD recommendations (ILCD Handbook, 2010). The recommendations from the Product Environmental Footprint (PEF) from the European Commission (EC) were also considered (Zampori & Pant. 2019).

LCA is a methodology used to evaluate the potential environmental impacts of products or services throughout their entire life cycle. LCA allows to: (i) evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used (inputs) and wastes released to the environment (outputs), and (ii) identify and assess opportunities to improve the environmental sustainability.

According to the ISO standard procedures, the LCA stages are: (1) goal and scope definition, (2) Life Cycle Inventory (LCI) analysis, (3) Life Cycle Impact Assessment (LCIA) and (4) interpretation of results (Figure 1).

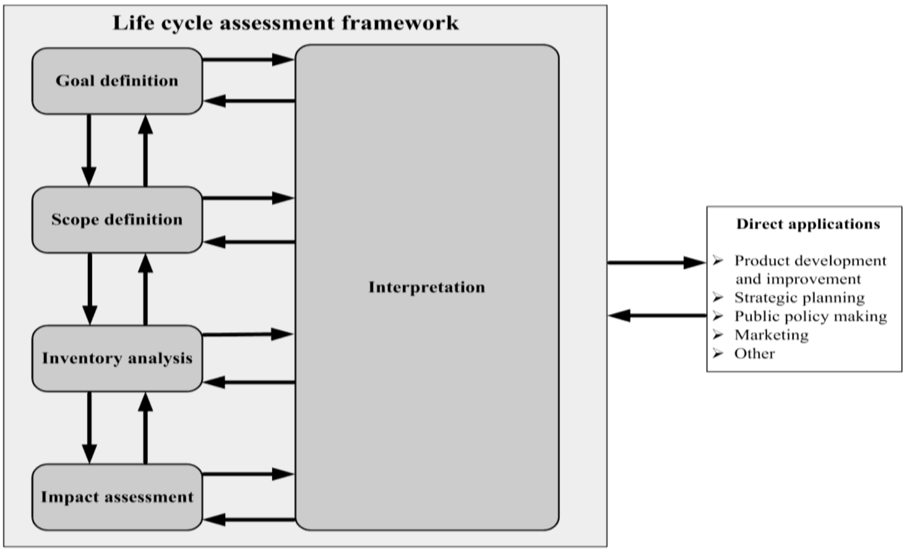

Figure 1- Framework for Life Cycle Assessment (source: ISO 14040, 2006).

In the Goal and Scope phase, the objective of the LCA study as well as the main parameters, such as functional unit, system boundaries and data quality, are defined. The Functional Unit (FU) is the quantification of the identified functions (performance characteristics) of the product; its primary purpose is to provide a reference for inputs and outputs. The System boundary defines the unit processes to be included in the system. Data quality defines the characteristics of data related to their ability to satisfy stated requirements.

The Life Cycle Inventory (LCI) analysis is the second phase of LCA. It consists of an inventory of all input/output flows with regard to the analyzed system. LCI involves (i) the collection of specific primary data necessary to characterize the foreground inventory, (ii) secondary data from the literature, and (iii) the selection of the most representative secondary background data, usually from average or generic LCI databases such as EcoInvent. In detail, data are collected for each unit process within the system boundaries.

The data collected may include:

- energy input, raw material input, ancillary input, other physical inputs;
- products, by-products and waste;
- releases to air, water and soil;
- other environmental aspects.

Life cycle impact assessment (LCIA) aims at evaluating the significance of potential environmental impacts of the investigated product, process or service, using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories. Examples of impact categories are Acidification, Climate change, Particulate matter, Eutrophication, Human toxicity, Ozone depletion and Water use. The LCIA phase provides information about impact contributions and the main hotspots (phase or inputs/outputs), which is useful for interpreting results.

The Interpretation of results is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together to understand the impact sources and their significance. The interpretation phase should deliver results consistent with the defined goal and scope, provide clear conclusions, explain limitations, suggest improvements and offer recommendations.

All the LCA phases may involve an iterative process of reviewing and revising the scope of the LCA analysis, as well as the nature and quality of the collected data, to ensure consistency with the defined goal.

2.1 **Goal and Scope**

The main LCA analysis objectives were:

1) to assess the environmental sustainability of the current biowaste management scenario (BaU);
2) to investigate the environmental performance of different alternative scenarios (Biochemicals and Bioenergy);
3) to identify drawbacks (hotspots) and benefits in both BaU and Alternative scenarios;
4) to compare the potential environmental performance of the BaU scenario with that of the selected alternative scenarios;
5) to evaluate the environmental advantages of using the bio-based products in place of their fossil counterparts.

The selected Functional Unit (FU) in the LCA analyses was 1 ton of forestry residues and wood processing waste (collectively referred to as residual biomass or biomass residues).

In LCA, the system boundaries typically refer to the extent of the life cycle considered for the assessment. "Cradle to gate" is a common system boundary used in LCA, encompassing the entire life cycle of a product or process from raw material extraction (cradle) to the point of leaving the manufacturing facility (gate). The "cradle to gate" system boundary includes all the stages involved in the life cycle, such as raw material acquisition, processing, manufacturing, packaging, and transportation up to manufacturing facility gate. It excludes the use phase, end-of-life considerations, and any subsequent stages beyond the manufacturing gate. By setting the system boundaries at "cradle to gate," the focus of the LCA is primarily on the environmental impacts and resource consumption associated with the production and manufacturing stages. These boundaries allow for a detailed assessment of the inputs, energy use, emissions, and waste generated during these stages, providing valuable insights into the environmental performance of a product or process until it leaves the manufacturing facility.

In this work, for all the investigated biowaste management scenarios, the system boundaries were selected according to a “Cradle to gate” approach, since the objective was to plan biocircular technological solutions to be developed and integrated in the local economy.

As described in Figure 2, in the BaU scenario, 65% of the forestry residues - after being grinded in the forest (wood chipping) - are transported and processed into pellets (60%) and compost (5%). The pelletizer process annually treats about 59,386 tons/yr, of which 43,267 tons coming from forest residues and the remaining part (16,119 tons) from wood processing waste. The pelletizing process transforms the forestry residues into compact and energy-dense pellets, suitable for the use as fuel in a wide range of applications (e.g. domestic and residential heating, but also for large boilers and in large thermoelectric power plant systems). Instead, the amount of forestry residues, treated in a composter, is about 3,606 tons/yr that are mixed with about 1,395 tons/yr of municipal biowaste (green waste) to produce about 4,000 tons/yr of compost that can be used instead of synthetic fertilizers. It is important to underline that a significant quantity of forestry residues (about 35%) is still unused and left on the ground, causing frequent fires.

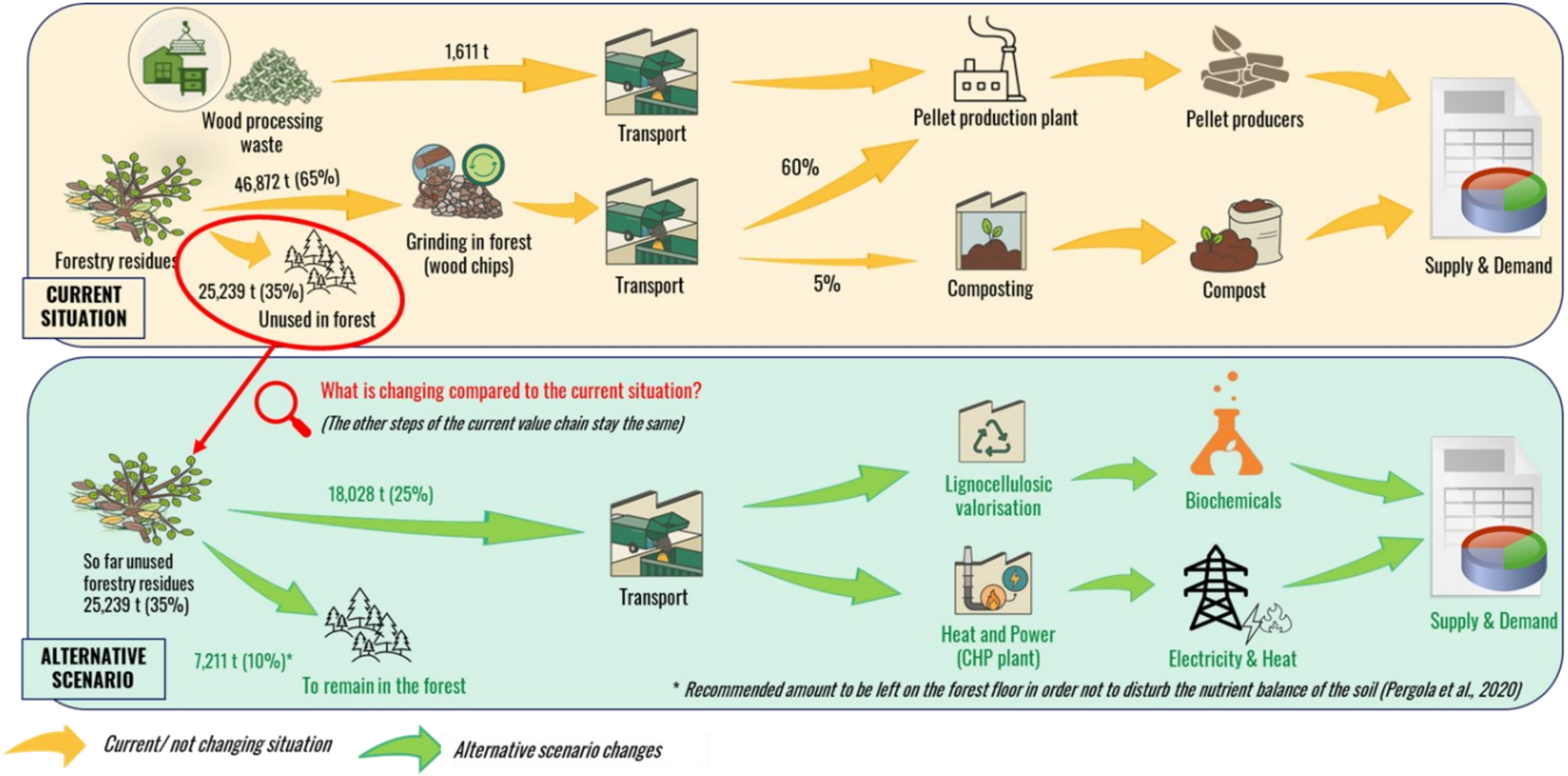

Figure 2. The forestry residues chain selected in the PP area.

Summarizing, the quantity of residues yearly produced (in 2019) in Pazardzhik forest is 1.3E+04 tons dry matter basis (d.m). Wood residues left on the soil correspond to 35% of this amount, equaling to almost 3 tons d.m. per hectare, considering a felling area of 4,228.5 ha.

Keeping in mind that forestry residues must be managed carefully to avoid disturbing forest ecosystem services and considering the best practices suggested by EU guidelines, two Alternative scenarios were designed and analysed for the PP pilot area (Figure 2).

In both Alternative scenarios, compared to the BaU scenario, a valorization of an additional 25% of forestry residues (unused in the BaU scenario) is carried out. Consequently, only 10% of forestry residues is left on the ground to preserve the soil ecosystem (Pergola et al., 2020; Pergola et al., 2022). Moreover, as in the BaU scenario, wood processing waste and 60% of forestry residues are valorized as pellets and 5% of forestry residues (mixed with biowaste from self-garden production) is converted into compost.

In the Alternative scenario called Biochemicals, the additional 25% of the total forestry residues undergoes lignocellulosic valorization for biochemicals production in a biorefinery plant. The production of different biochemicals was accounted for and average data were used (Fiorentino et al., 2014; Forte et al., 2016; Zucaro et al., 2017), in order to promote the transferability of the results to other European contexts. A schematic step-by-step flow chart is presented in Figure 3. Moreover, a detailed description of the analyzed biochemical production processes is reported in Fiorentino et al. (2014), Forte et al. (2016) and Zucaro et al. (2017).

In the second Alternative scenario, referred to as Bioenergy and strongly suggested by the local stakeholders during the first local Living Lab, the additional 25% of forestry residues (unused in the BaU scenario) is processed into electricity and heat in a CHP plant, replacing the fossil fuels (Figure 4).

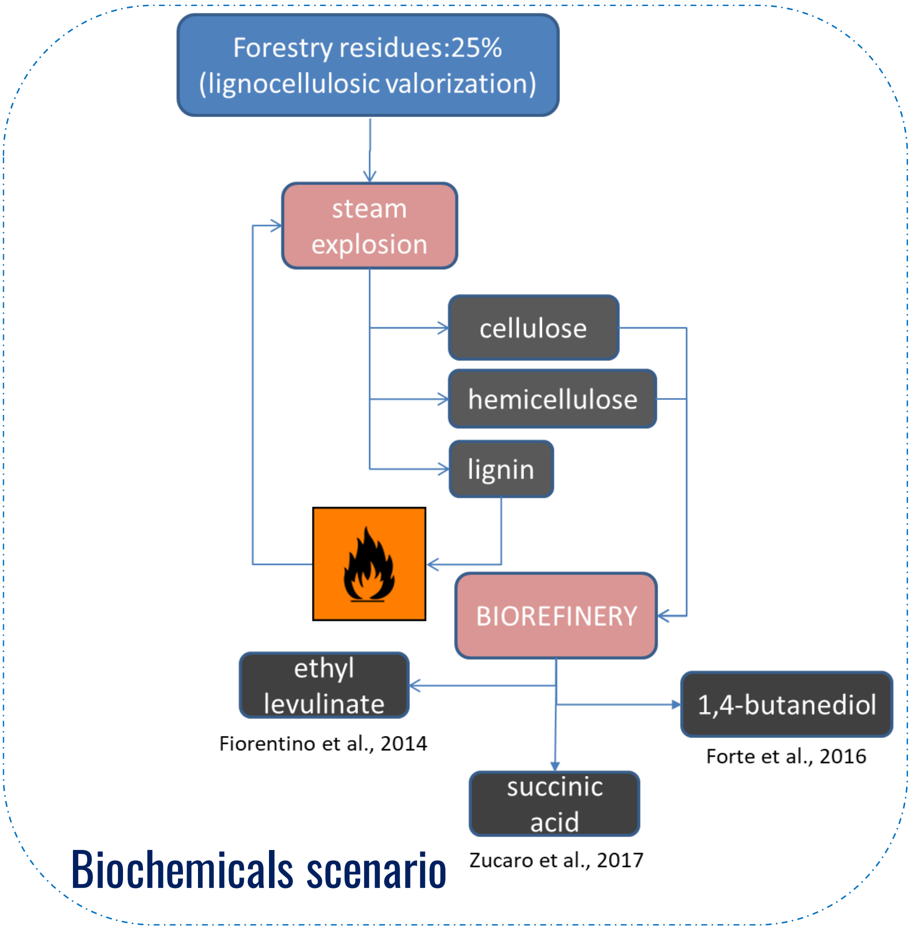

Figure 3 - Schematic description of the Biochemicals Alternative scenario.

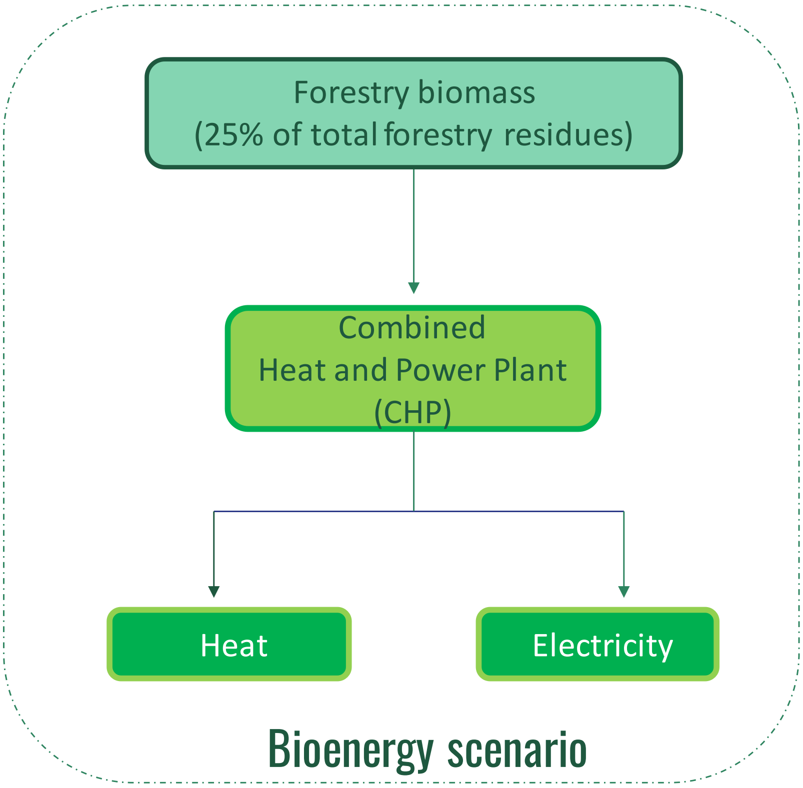

Figure 4 - Schematic description of the Bioenergy Alternative scenario.

2.1.1 Assumptions and limitations of the PP pilot area

The main calculations and assumptions made in the Biochemicals Alternative scenario were:

- forestry residues generation has no impact, according to a zero-burden approach (Ekvall et al, 2000);
- an average distance of 10 km (as in the BaU scenario) is assumed for collection and transportation of 25% of forestry residues to a local biorefinery plant;
- the biorefinery plant includes: (i) steam explosion pre-treatment (Fiorentino et al., 2014, Zucaro et al. 2017) to convert lignocellulosic residues into hydrolyzed celluloses (C6 sugars), hemicelluloses (C5 sugars) and lignin fraction (used to partially supply the energy consumption of biorefinery processes) and (ii) a chemical process (Fiorentino et al., 2014, Forte et al., 2016, Zucaro et al., 2017) to convert lignocellulosic C5 and C6 sugars into three different biochemicals: Ethyl levulinate-EL (Fiorentino et al., 2014), 1,4 Butanediol - BDO (Forte et al., 2016) and Succinc acid- SA (Zucaro et al.; 2017);
- an average between 74% and 100% recovery efficiency of total sugars after pre-treatment is assumed (Forte et al., 2016, Zucaro et al., 2017);
- the quantity of forestry residues (25% of total forestry residues produced) is divided into three equal parts (33% each) for the production of the three biochemicals EL, BDO and SA;
- for the calculation of net impacts, the avoided production of equal quantities of fossil chemical counterparts is considered. In particular, the "Butane-1,4-diol {GLO}| market for | APOS, U" is used to credit the production of bio-BDO and the "Succinic acid {GLO}| market for succinic acid | APOS, U" is used to credit the production of bio-SA. As far as Ethyl levulinate (EL) is concerned, due to its absence in the EcoInvent database, "Ethyl acetate {GLO}| market for | APOS, U" (50% of the total produced bio-EL) and "Butyl acetate {RER}| market for butyl acetate | APOS, U" (50% of the total produced bio-EL) are used as proxy for the credit obtained by the production of bio-EL (Fiorentino et al., 2019).

The main calculations and assumptions made in the Bioenergy alternative scenario were:

- transportation of forestry residues to the local CHP plant is considered on 10 km, as in the BaU scenario (10km/journey).
- according to EcoInvent 3.8 database, the LHV of forestry residues is 18.9 MJ/kg;
- according to EcoInvent 3.8 database, the CHP plant losses are set to 40%;
- according to EcoInvent 3.8 database, Electricity produced is 15% of the obtainable energy;
- according to EcoInvent 3.8 database, Heat produced is 45% of the obtainable energy;
- heat and electricity produced in the CHP plant are assumed to be entirely used to replace fossil energy counterparts (namely electricity from CHP plant replaces the national electricity mix, whereas the heat produced from CHP plant replaces an equal amount of heat produced from fossil natural gas).

It is worth noting that the conversion of 25% of forestry residues into added value products (biochemicals or thermal and electrical energy) represents the maximum exploitable quantity of unused forestry residues. Indeed, according to the feedback received from the Experts during the 3rd Peer Review Session of the BCC project, to ensure the protection of the soil ecosystem, it would be advisable to leave 20% of forestry residues on the ground. In the latter case, therefore, only 15% could be valorized through the alternative scenarios proposed in this study (Biochemicals and

Bioenergy scenarios). Consequently, the environmental and economic impacts, resulting from the LCA and LCC analyses, would decrease proportionally.

2.1.2 Data sources

In order to assess the environmental impacts of the BaU and Alternative scenarios, primary data (site-specific data) were asked to the local partner, REAP, through *ad hoc* questionnaires. In detail, information on energy and material consumption, emissions and waste production, waste management, and the amount of recovered materials were requested. The time reference for BaU primary data was 2019.

The data not provided by the local partners were replaced with data from the scientific literature (background/secondary data) and/or from the EcoInvent 3.8 database (https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-8/). Background data related to energy generation, use of energy, auxiliary materials and impacts of waste management (wastewater treatment) and airborne/waterborne emissions were derived from EcoInvent ("allocation at point of substitution, unit processes" datasets). Averaged European or global data were used for materials and chemicals, while, for the supply of electricity, the medium-voltage electric mix specific for Bulgaria was selected.

In particular, for the BaU scenario, primary data, for all the investigated steps, starting from the collection up to the final products (pellets and compost) and including the transportation, were provided by the local partner (REAP). It was not possible to estimate the Soil Carbon Storage (SCS) for the unused forestry residues left on the ground because site-specific humification factors were unavailable, and the information on soil humidity and temperature was incomplete and not exhaustive. Therefore, estimating soil hydraulic properties and/or annual mineralization rates was not feasible. Furthermore, according to forestry experts, it was not possible to run soil C models or use any specific function to depict C dynamics in the pilot area of Pazardzhik, since the duration of these processes is very long (up to 100 years) and an annual SCS estimation would not be realistic.

On the other hand, for both Alternative scenarios, due to the lack of primary data, a careful analysis of the pertinent scientific literature and of specialized LCA databases was carried out. Specifically, for Biochemicals scenario, energy and material inputs for the steam explosion pre-treatment were retrieved from the EcoInvent database v.3.8 and pertinent scientific literature (Fiorentino et al., 2014, Zucaro et al. 2017). Moreover, energy, nutrients and chemicals related to the fermentation and purification steps were retrieved from Fiorentino et al. (2014) for bio-EL, from Forte et al. (2016) for bio-BDO, and from Zucaro et al. (2017) for bio-SA. Finally, the average forestry residues composition was assumed as follows: 44% cellulose, 26% hemicellulose, 25% lignin, 1% ashes and 4% other organics and extractives (based on estimation from REAP).

For the treatment process (CHP plant), in the Bioenergy scenario, secondary data from EcoInvent 3.8 database were retrieved. In detail, to overcome the lack of primary data for CHP plant, the unit processes from EcoInvent 3.8, "Electricity, high voltage {BG}| heat and power co-generation, wood chips, 6667 kW | APOS, U" and "Heat, district or industrial, other than natural gas {BG}| heat and power co-generation, wood chips, 6667 kW | APOS, U" were adopted.

For the three investigated scenarios (BaU, Biochemicals and Bioenergy), the amount of nitrogen (N), potassium (K) and phosphorus (P) releasable from compost were those reported in the ECN DATA REPORT (Gilbert & Siebert, 2022) and an equivalent avoided production of synthetic fertilizers (inorganic nitrogen fertilizer, inorganic phosphorus fertilizer and inorganic potassium fertilizer) was considered .

2.1.3 Impact assessment software and method

The Professional software SimaPro 9.5.0.0 (Pre-Consultants) was used for calculations and coupled to the Environmental Footprint (EF) 3.1 (adapted) V1.00 impact assessment method (Andreasi Bassi et al., 2023; Fazio et al., 2018). The EF is an impact assessment method developed by the European Commission (EC) with the aim of providing standardized and harmonized impact assessment practices across different European sectors and regions.

The EF method evaluates multiple midpoint impact categories such as climate change, resource depletion, and water use, allowing for a holistic understanding of environmental performance. The selected impact categories for the LCA analyses of the investigated scenarios are listed in Table 2.

Table 2. Environmental Footprint impact categories selected for the BCC LCA studies (Andreasi Bassi et al., 2023).

Selected impact categories	Unit	Abbreviation
Acidification	mol H^+ eq	AC
Climate change	kg CO_2 eq	CC
Particulate matter	disease incidence	PM
Eutrophication, marine	kg N eq	EM
Eutrophication, freshwater	kg P eq	EF
Eutrophication, terrestrial	mol N eq	ET
Human toxicity, cancer	CTUh	HTc
Human toxicity, non-cancer	CTUh	HTnc
Ozone depletion	kg CFC_{11} eq	OD
Photochemical ozone formation	kg NMVOC eq	POF
Resource use, fossils	MJ	RUF
Resource use, minerals and metals	kg Sb eq	RUM
Water use	m^3 depriv.	WU

2.2 Life Cycle Inventory (LCI) of the PP pilot area

Table 3 reports the main foreground input and output material and energy flows involved in the investigated BaU scenario, with reference to the selected functional unit (1 ton of residues from forestry and wood processing). The total amount of residues from forestry (72,111 tons/yr wet basis) and wood processing (16,119 tons/yr wet basis) treated in the reference year (2019) amounts to 88,230 tons/yr of which: (i) 60% of forestry residues is used for pellet production (43,267 tons/yr wet basis) mixed with wood processing residues (16,119 tons/yr wet basis), (ii) 5% of forestry residues is used for compost production (3,606 tons/yr wet basis) and (iii) 35% of forestry biomass is left on the ground (2.52E+04 tons/yr wet basis).

Table 3 - Life Cycle Inventory for BaU scenario in the PP pilot area, referred to the FU of 1 ton of residues from forestry and wood processing.

Forestry residues and wood processing waste in the PP pilot area			
BaU scenario - Biomass left on the ground (35% of forestry residues)			
Inputs	**Unit/FU**	**Value**	**Reference**
Brush-wood (wetness is about 40-60%)	kg wet basis	9.22	Primary data-REAP
Twigs (50% wetness)	kg wet basis	57.31	Primary data-REAP
Wood loppings (55% wetness)	kg wet basis	117.65	Primary data-REAP
Bark (45% wetness)	kg wet basis	57.72	Primary data-REAP
Stubs (40-50% wetness)	kg wet basis	44.16	Primary data-REAP
Total forestry residues	kg wet basis	286.06	

BaU scenario – Pellet production (60% of forestry residues + wood processing waste)

Inputs	**Unit/FU**	**Value**	**Reference**
Brush-wood (wetness is about 40-60%)	kg wet basis	15.81	Primary data-REAP
Twigs (50% wetness)	kg wet basis	98.25	Primary data-REAP
Wood loppings (55% wetness)	kg wet basis	201.68	Primary data-REAP
Bark (45% wetness)	kg wet basis	98.95	Primary data-REAP
Stubs (40-50% wetness)	kg wet basis	75.70	Primary data-REAP
Total of forestry residues	kg wet basis	490.38	
Dry shavings (15% wetness)	kg wet basis	99.95	Primary data-REAP
Dry sawdust (15% wetness)	kg wet basis	59.50	Primary data-REAP
Sander dust (15% wetness)	kg wet basis	23.23	Primary data-REAP
Total of wood processing waste	kg wet basis	182.69	
Transport	tkm	6.73	Primary data-REAP
Grinding machine - BC 2000 XL Vermeer			Primary data-REAP
daily working	hours/day	4.53E-05	Primary data-REAP
working days	Days/yr	1.36E-03	Primary data-REAP
lifetime	years	2.83E-04	Primary data-REAP
Wood chipping, chipper, mobile, diesel, at forest road {GLO}| market for | APOS, U	working hours	1.70E-01	Secondary data-EcoInvent 3.8
Drying Furnace for Wood Chips			Primary data -REAP
Wood density	kg/m^3	750.00	Secondary data-EcoInvent 3.8
Technical wood drying facility {GLO}| market for | APOS, U	Number of machinery	1	Secondary data-EcoInvent 3.8
Electricity consumption	kWh/yr	0.68	Primary data-REAP
Heat consumption	kWh/yr	1.08	Primary data-REAP
Water consumption	m^3/yr	0.01	Primary data-REAP
Outputs	**Unit/FU**	**Value**	**Reference**
Pellets produced and sold to the market	tons/yr	0.51	Primary data REAP
Waste disposal	tons/yr	0.01	Primary data - REAP
Wastewater	m^3/yr	6.74E-03	Primary data - REAP

BaU scenario – Compost production (5% of forestry residues)

Inputs	**Unit/FU**	**Value**	**Reference**
Brush-wood (wetness is about 40-60%)	kg wet basis	1.32	Primary data - REAP
Twigs (50% wetness)	kg wet basis	8.19	Primary data - REAP
Wood loppings (55% wetness)	kg wet basis	16.81	Primary data - REAP
Bark (45% wetness)	kg wet basis	8.25	Primary data - REAP
Stubs (40-50% wetness)	kg wet basis	6.31	Primary data - REAP
Total of forestry residues	kg wet basis	40.87	Primary data - REAP
Biomass from municipal and self-garden production	kg wet basis	0.02	Primary data - REAP
Transport	tkm	0.03	Primary data - REAP
Grinding machine - BC 2000 XL Vermeer			
daily working	hours/day	4.53E-05	Primary data - REAP
working days	Days/yr	1.36E-03	Primary data - REAP
lifetime	years	2.83E-04	Primary data - REAP
Wood chipping, chipper, mobile, diesel, at forest road {GLO}| market for | APOS, U	working hours	1.70E-01	Secondary data - EcoInvent 3.8
Composter			
Biowaste {CH}| treatment of biowaste, industrial composting | APOS, U	tons/yr	0.05	Secondary data - EcoInvent 3.8
Electricity consumption	kWh/yr	0.23	Primary data - REAP
Heat consumption	kWh/yr	0.28	Primary data - REAP
Water consumption	m^3/yr	3.63E-03	Primary data - REAP
Outputs	**Unit/FU**	**Value**	**Reference**
Compost produced and sold to the market	tons/yr	0.05	Primary data - REAP

For both alternative scenarios, Biochemicals and Bioenergy, an additional 25% of forestry residues (1.80E+04 tons/yr wet basis or 8.98E+03 tons/yr dry basis) was valorized in a local biorefinery, for biochemicals production, and in a local CHP plant, for energy production, respectively. Therefore, in these alternative scenarios, only 10% (2.52E+03 tons/yr wet basis) of forestry residues is left on the field. On the other hand, the production of pellets (60% of forestry residues plus 16,119 tons/yr wood processing residues) and compost (5% of forestry residues) remains the same as presented in the BaU scenario (see Table 3 for details).

In Table 4, the input and output flows for Biochemicals productions, referred to the selected functional unit (1 ton of residues from forestry and wood processing), are reported.

Table 4 - Life Cycle Inventory for Biochemicals scenario in the PP pilot area, referred to the FU of 1 ton of residues from forestry and wood processing.

Biochemicals scenario - bio-Ethyl levulinate

Inputs	**Unit/FU**	**Value**	**Reference**
Hydrolyzed celluloses and hemicelluloses	kg dry basis	61.64	Secondary data- Forte et al., 2016, Zucaro et al., 2017
Electricity, medium voltage	MJ	60.02	Secondary data-Fiorentino et al., 2014; EcoInvent 3.8
Steam, for chemical processes	kg	0.32	Secondary data-Fiorentino et al., 2014; EcoInvent 3.8
Water, ultrapure	kg	2.99	Secondary data-Fiorentino et al., 2014; EcoInvent 3.8
Sulfuric acid, liquid	kg	0.62	Secondary data-Fiorentino et al., 2014; EcoInvent 3.8
Sodium hydroxide, 50% in H_2O	kg	0.09	Secondary data-Fiorentino et al., 2014; EcoInvent 3.8
Ethanol from ethylene	kg	6.16	Secondary data-Fiorentino et al., 2014; EcoInvent 3.8
Hydrogen, liquids	kg	0.02	Secondary data-Fiorentino et al., 2014; EcoInvent 3.8
Outputs	**Unit/FU**	**Value**	**Reference**
Bio-Ethyl levulinate	kg	7.74	Fiorentino et al., 2014

Biochemicals scenario – bio-Succinc acid (bio-SA)

Inputs	**Unit/FU**	**Value**	**Reference**
Hydrolyzed celluloses and hemicelluloses	kg dry basis	61.64	Forte et al., 2016, Zucaro et al., 2017
Water	kg	730.58	Secondary data- Zucaro et al., 2017; EcoInvent 3.8
Nutrients and other organic/inorganic chemicals	kg	25.11	Secondary data- Zucaro et al., 2017; EcoInvent 3.8
Total energy consumption1	MJ	342.46	Secondary data- Zucaro et al., 2017
Outputs	**Unit/FU**	**Value**	**Reference**
Bio-Succinc acid	kg	7.53	Secondary data- Zucaro et al., 2017
Wastewater to WWTP	m^3	6.85E-04	Secondary data- Zucaro et al., 2017; EcoInvent 3.8
Sludge	kg	0.09	Secondary data- Zucaro et al., 2017; EcoInvent 3.8

Biochemicals scenario – bio-1,4 Butanediol (bio-BDO)

Inputs	**Unit/FU**	**Value**	**Reference**
Hydrolyzed celluloses and hemicelluloses	kg dry basis	61.64	Forte et al., 2016, Zucaro et al., 2017
Water	kg	687.55	Secondary data- Forte et al., 2016; EcoInvent 3.8
Sulphuric acid	kg	7.11	Secondary data- Forte et al., 2016; EcoInvent 3.8
Nutrients and organic chemicals	kg	35.56	Secondary data- Forte et al., 2016; EcoInvent 3.8
Quicklime	kg	5.93	Secondary data- Forte et al., 2016; EcoInvent 3.8

Total energy consumption[2]	MJ	4860.26	Secondary data- Forte et al., 2016; EcoInvent 3.8
Outputs	**Unit/FU**	**Value**	**Reference**
Bio-BDO	kg	39.12	Secondary data- Forte et al., 2016; EcoInvent 3.8

[1] The plant appeared self-sufficient for EE and heat through combustion of unconverted solid (Zucaro et al., 2017).

[2] The plant appeared self-sufficient (through combustion of unconverted solid in CHP) for EE input whilst an additional amount of 2.02E+03 MJ of heat per FU was required and assumed supplied to the system by natural gas burning (Forte et al., 2016).

The data inventory for the Bioenergy scenario are not shown since, as explained in the section 2.1.2 (Data sources), they were retrieved from EcoInvent v.3.8.

2.3 Life cycle impact assessment (LCIA) of the PP pilot area

The LCIA analysis allows to compare the impact generated by different systems (same FU) and to identify the hotpots, highlighting, for each impact category, the most impacting phase. The impacts generated from the comparison among the BaU and the two Alternative scenarios (Biochemicals and Bioenergy) are shown in Table 5 and Figure 5.

Table 5 - Comparison among the total characterized impacts for the investigated scenarios in the PP pilot area: BaU, Bioenergy, Biochemicals. Impacts are referred to 1 ton of residues from forestry and wood processing (FU).

Impact category (IC)	Abbrev.	Unit	BaU	Bioenergy	Biochemicals
Acidification	AC	mol H+ eq	9.94E-02	-4.01E-01	-7.51E-01
Climate change	CC	kg CO_2 eq	1.70E-02	-8.34E+01	-1.27E+02
Particulate matter	PM	disease inc.	5.60E-07	-4.08E-06	-8.73E-06
Eutrophication, marine	EM	kg N eq	3.70E-03	-1.52E-02	-1.41E-01
Eutrophication, freshwater	EF	kg P eq	3.77E-04	-9.96E-02	-3.74E-02
Eutrophication, terrestrial	ET	mol N eq	4.88E-01	5.57E-01	-1.07E+00
Human toxicity, cancer	HTc	CTUh	-1.61E-10	-4.32E-08	-1.18E-07
Human toxicity, non-cancer	HTnc	CTUh	-9.01E-09	-8.24E-07	-1.50E-06
Ozone depletion	OD	kg CFC11 eq	-1.38E-07	-8.48E-06	-1.57E-05
Photochemical ozone formation	POF	kg NMVOC eq	1.12E-03	-3.15E-02	-5.19E-01
Resource use, fossils	RUF	MJ	-2.68E+01	-1.39E+03	-2.13E+03
Resource use, minerals and metals	RUM	kg Sb eq	-6.43E-05	-1.38E-04	-1.34E-03
Water use	WU	m^3 depriv.	-2.05E+00	-9.32E+01	-3.91E+02

From the comparison among the three scenarios, the Alternative scenarios prove to be more advantageous from an environmental point of view in all investigated impact categories. In particular, the most relevant benefit for Biochemicals scenario is recorded in ET impact category, since this impact category is strongly affected by the wastewater resealed in the environment in the pellet production (BaU scenario) and in the cogeneration process (Bioenergy scenario). In Figure 5, for almost all investigated impact categories, the environmental loads (the bars above the red line) generated in the Alternative scenarios are negligible compared to the benefits (the bars below the red line) coming from the avoided production of fossil chemicals (in the case of Biochemicals scenario) or from the avoided production of fossil energy (in the case of Bioenergy scenario). In particular, the Biochemicals scenario shows higher potential environment benefits than the Bioenergy scenario, in EM, ET, POF, RUM and WU (89%, 152%, 94%, 90% and 76% respectively).

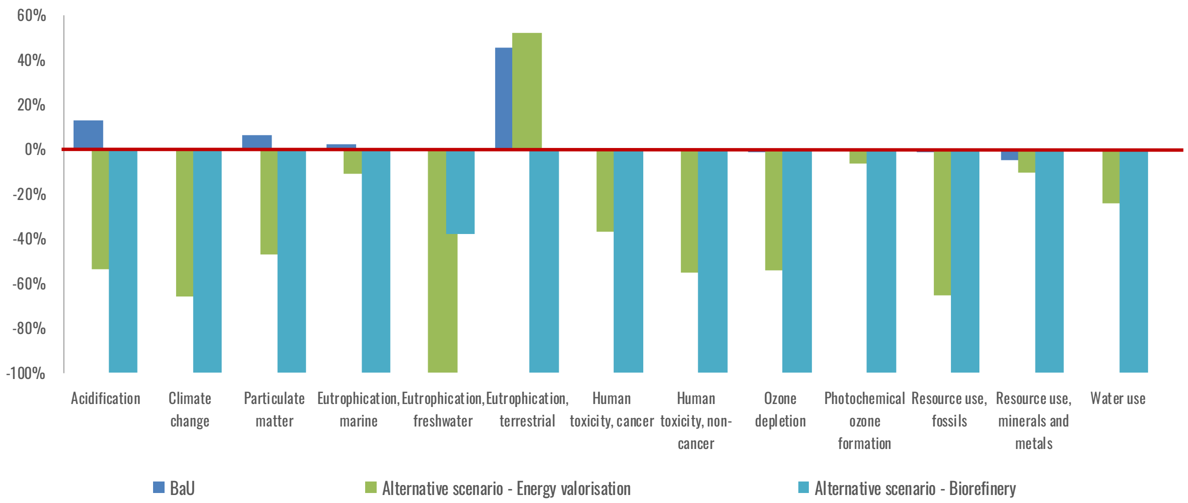

Figure 5 - Comparison of characterized impacts for 1 ton of residues from forestry and wood processing (FU) for the investigated scenarios: BaU, Alternative Bioenergy, Alternative Biochemicals.

For the BaU scenario (Table 6) the highest burdens are related to the conversion process of forestry residues into compost. However, the benefits provided from the avoided production of N, P, K fossil fertilizers partially balance the environmental loads (Figure 6). Specifically, net benefits are recorded in HTc, HTnc, OD, RUF and RUM, mainly due to the avoided production of N fertilizers.

Table 6 - Characterized impacts, referred to the FU of 1 ton of residues from forestry and wood processing, calculated for the BaU scenario of the PP pilot area: total impacts and impacts split over each process.

IC	Total BaU scenario	Biomass left on the ground	Pellets production	Compost production	Avoided N Fertilizers	Avoided P Fertilizers	Avoided K Fertilizers
AC	9.94E-02	0.00E+00	7.75E-03	1.25E-01	-1.57E-02	-9.28E-03	-8.56E-03
CC	1.70E-02	0.00E+00	1.18E+00	2.93E+00	-2.43E+00	-4.30E-01	-1.24E+00
PM	5.60E-07	0.00E+00	1.53E-07	6.58E-07	-1.14E-07	-4.40E-08	-9.39E-08
EM	3.70E-03	0.00E+00	1.87E-03	5.37E-03	-1.94E-03	-3.80E-04	-1.21E-03
EF	3.77E-04	0.00E+00	8.91E-04	4.06E-04	-4.09E-04	-2.39E-04	-2.73E-04
ET	4.88E-01	0.00E+00	1.84E-02	5.50E-01	-4.72E-02	-5.86E-03	-2.70E-02
HTc	-1.61E-10	0.00E+00	5.63E-10	1.67E-09	-1.32E-09	-2.96E-10	-7.75E-10
HTnc	-9.01E-09	0.00E+00	1.64E-08	2.13E-08	-2.53E-08	-6.24E-09	-1.51E-08
OD	-1.38E-07	0.00E+00	1.92E-07	2.14E-07	-3.21E-07	-5.43E-08	-1.69E-07
POF	1.12E-03	0.00E+00	5.37E-03	5.24E-03	-4.71E-03	-1.48E-03	-3.28E-03
RUF	-2.68E+01	0.00E+00	1.93E+01	1.88E+01	-3.95E+01	-6.67E+00	-1.87E+01
RUM	-6.43E-05	0.00E+00	2.05E-06	6.68E-06	-4.19E-05	-7.77E-06	-2.33E-05
WU	-2.05E+00	0.00E+00	5.16E-01	2.92E-01	-1.94E+00	-3.88E-01	-5.23E-01

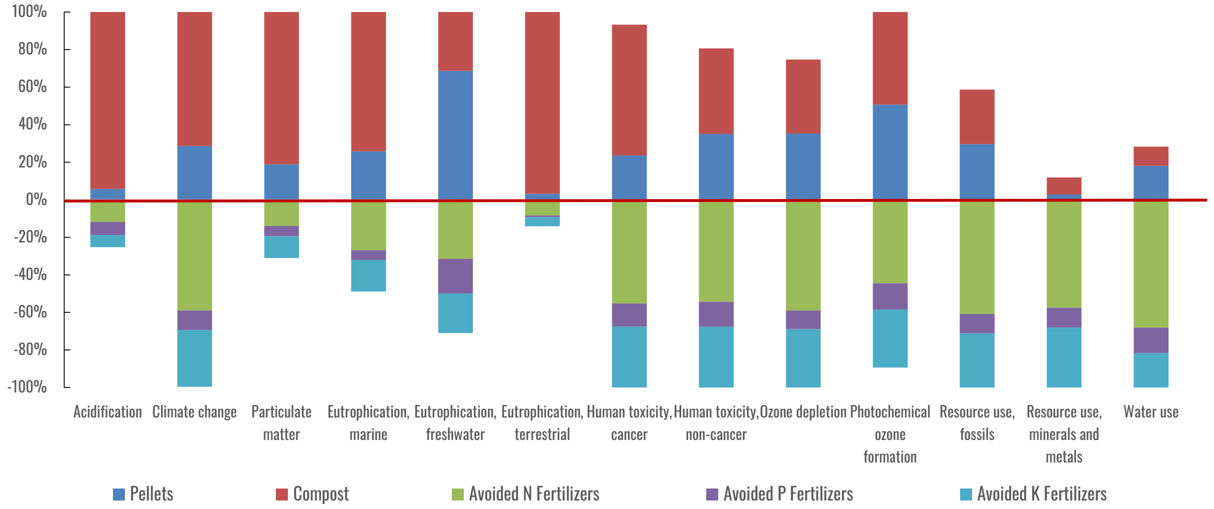

Figure 6 - Percentage contributions of each process including the avoided production of fossil fertilizers to total impacts of BaU scenario system for each impact category.

The analysis of the Biochemicals scenario (Table 7 and Figure 7) reveals that in almost all the investigated impact categories, the environmental loads are mainly due to the following lignocellulosic conversion processes: (i) the steam explosion pre-treatment for the conversion of forestry residues into hydrolyzed sugars (C5 and C6) and (ii) the chemical process to obtain the biochemicals (bio-EL, bio-SA and bio-BDO).

Table 7 - Characterized impacts, referred to the FU of 1 ton of residues from forestry and wood processing, calculated for Biochemicals scenario of the PP pilot area: impacts split over each process.[1]

IC	Pellets production	Compost production	Biochemicals -EL	Biochemicals - BDO	Biochemicals - SA	Transport	Avoided N,P,K Fertilisers	Avoided fossil SA	Avoided fossil BDO	Avoided fossil - EL
AC	7.75E-03	1.25E-01	8.97E-02	1.94E-01	6.93E-02	4.66E-04	-3.36E-02	-1.03E-01	-9.60E-01	-1.40E-01
CC	1.18E+00	2.93E+00	1.34E+01	7.56E+01	1.23E+01	9.10E-02	-4.10E+00	-2.44E+01	-1.79E+02	-2.51E+01
PM	1.53E-07	6.58E-07	3.39E-07	1.62E-06	8.63E-07	1.11E-08	-2.52E-07	-8.86E-07	-9.97E-06	-1.27E-06
EM	1.87E-03	5.37E-03	1.38E-02	3.05E-02	1.40E-02	1.60E-04	-3.53E-03	-1.72E-02	-1.63E-01	-2.35E-02
EF	8.91E-04	4.06E-04	2.56E-02	6.34E-03	2.92E-03	5.69E-06	-9.21E-04	-4.83E-03	-5.94E-02	-8.40E-03
ET	1.84E-02	5.50E-01	9.31E-02	3.29E-01	1.36E-01	1.75E-03	-8.01E-02	-1.82E-01	-1.69E+00	-2.49E-01
HTc	5.63E-10	1.67E-09	4.05E-09	3.28E-08	1.16E-08	2.84E-11	-2.39E-09	-1.88E-08	-1.37E-07	-1.13E-08
HTnc	1.64E-08	2.13E-08	2.05E-07	2.79E-07	1.49E-07	9.77E-10	-4.67E-08	-1.68E-07	-1.65E-06	-3.04E-07
OD	1.92E-07	2.14E-07	2.98E-07	7.73E-06	1.26E-06	2.21E-08	-5.44E-07	-4.72E-06	-1.67E-05	-3.47E-06
POF	5.37E-03	5.24E-03	3.44E-02	1.43E-01	4.68E-02	5.21E-04	-9.48E-03	-6.56E-02	-5.73E-01	-1.07E-01
RUF	1.93E+01	1.88E+01	2.99E+02	1.46E+03	3.09E+02	1.44E+00	-6.49E+01	-5.03E+02	-3.09E+03	-5.87E+02
RUM	2.05E-06	6.68E-06	4.33E-05	2.28E-04	1.59E-04	1.96E-07	-7.30E-05	-1.73E-04	-1.27E-03	-2.59E-04
WU	5.16E-01	2.92E-01	4.48E+00	2.59E+01	1.52E+01	5.09E-03	-2.85E+00	-5.30E+00	-4.07E+02	-2.19E+01

[1] The total impacts for the Alternative Biochemicals scenario are reported in the comparison Table (Table 5).

In details, the conversion processes (pre-treatment and acid hydrolysis) for the production of bio-EL were responsible for an average environmental load of 7%, while the production of bio-SA and the production of bio-BDO generated average environmental burdens of 6% and 18%, respectively. Instead, the harmful impacts from pellets and compost production as well as transport can be considered negligible (from 0% to 4%).

However, it is important to underline that the avoided production of fossil chemicals (fossil EL, fossil SA and fossil BDO) and, in particular, of fossil BDO brings net benefits (below the red line) to all the investigated impact categories.

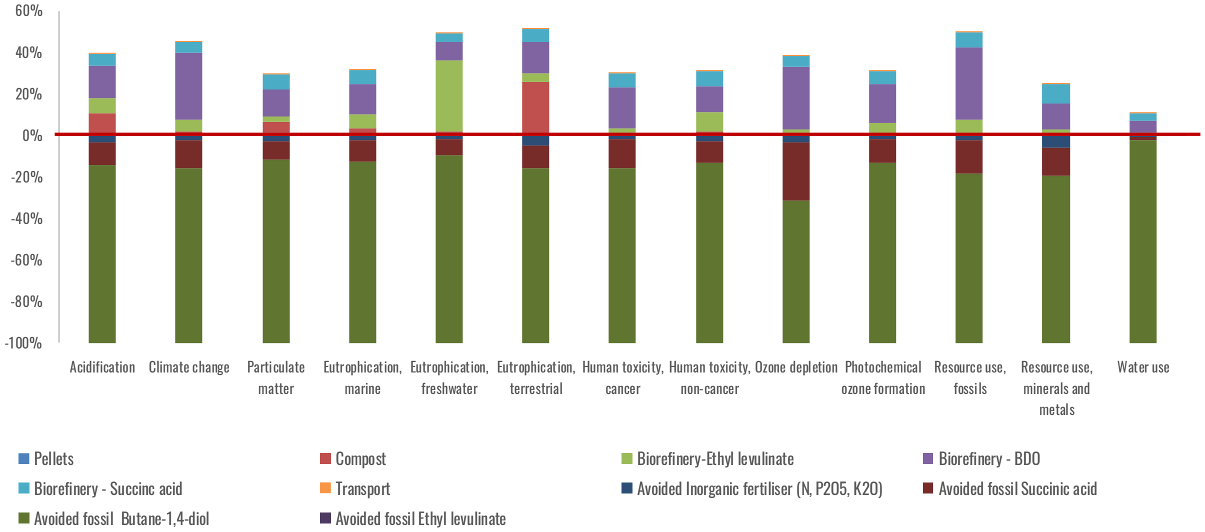

Figure 7 - Percentage contributions of Biochemicals scenario for each process including the avoided productions of fossil counterparts. FU is 1 ton of residues from forestry and wood processing.

After all, the evaluation of Bioenergy scenario (Table 8 and Figure 8) points out some environmental benefits (negative bars), deriving from the avoided production of electricity from national mix (-36% as average net benefit in all the investigated impact categories) and of heat from natural gas (-55% as average net benefit in all the investigated impact categories). Indeed, thanks to the electrical and thermal energy produced by the cogeneration plant and sold to the grid and, at a minor extent, to the avoided production of fossil N, P, K fertilizers (-7% as net average benefit, considering all the investigated impact categories), a net benefit is reported for this scenario. In particular, the avoided production of fossil fertilizers produces a significant advantage in the RUM impact category (-47%). Regarding environmental loads, the CHP plant is the main contributor, producing a more marked impact in the EM (83%) and POF (88%) impact categories.

Table 8 - Characterized impacts, referred to the FU of 1 ton of residues from forestry and wood processing, calculated for the Alternative Bioenergy scenario of the PP pilot area: total impacts and impacts split over each process.

IC	Total Bioenergy scenario	Pellets production	Compost production	CHP process	Transport	Avoided N,P,K Fertilisers	Avoided Electricity, medium voltage	Avoided natural gas
AC	7.75E-03	1.25E-01	8.97E-02	1.94E-01	6.93E-02	4.66E-04	-3.36E-02	-1.03E-01
CC	1.18E+00	2.93E+00	1.34E+01	7.56E+01	1.23E+01	9.10E-02	-4.10E+00	-2.44E+01
PM	1.53E-07	6.58E-07	3.39E-07	1.62E-06	8.63E-07	1.11E-08	-2.52E-07	-8.86E-07
EM	1.87E-03	5.37E-03	1.38E-02	3.05E-02	1.40E-02	1.60E-04	-3.53E-03	-1.72E-02
EF	8.91E-04	4.06E-04	2.56E-02	6.34E-03	2.92E-03	5.69E-06	-9.21E-04	-4.83E-03
ET	1.84E-02	5.50E-01	9.31E-02	3.29E-01	1.36E-01	1.75E-03	-8.01E-02	-1.82E-01
HTc	5.63E-10	1.67E-09	4.05E-09	3.28E-08	1.16E-08	2.84E-11	-2.39E-09	-1.88E-08
HTnc	1.64E-08	2.13E-08	2.05E-07	2.79E-07	1.49E-07	9.77E-10	-4.67E-08	-1.68E-07
OD	1.92E-07	2.14E-07	2.98E-07	7.73E-06	1.26E-06	2.21E-08	-5.44E-07	-4.72E-06
POF	5.37E-03	5.24E-03	3.44E-02	1.43E-01	4.68E-02	5.21E-04	-9.48E-03	-6.56E-02
RUF	1.93E+01	1.88E+01	2.99E+02	1.46E+03	3.09E+02	1.44E+00	-6.49E+01	-5.03E+02

RUM	2.05E-06	6.68E-06	4.33E-05	2.28E-04	1.59E-04	1.96E-07	-7.30E-05	-1.73E-04
WU	5.16E-01	2.92E-01	4.48E+00	2.59E+01	1.52E+01	5.09E-03	-2.85E+00	-5.30E+00

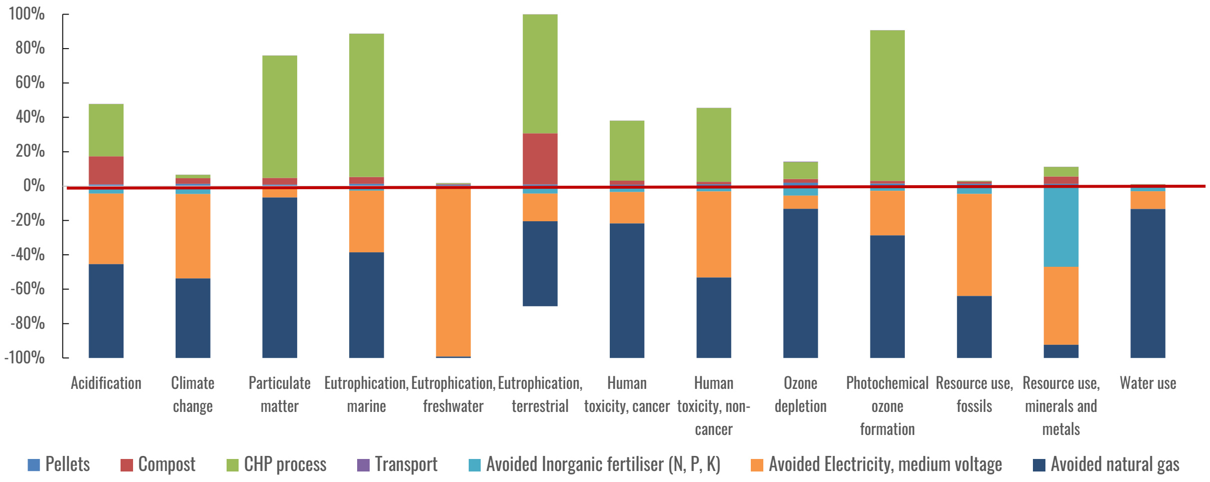

Figure 8 - Percentage contributions of Bioenergy scenario for each process, including the avoided productions of fossil counterparts. FU is 1 ton of residues from forestry and wood processing.

3. LIFE CYCLE COSTING (LCC) OF THE BIOWASTE MANAGEMENT SYSTEMS IN THE THREE PILOT AREAS

Life Cycle Costing (LCC) is applied as an assessment tool to estimate the entire cost of the system under investigation, during its whole life cycle. As a cost-oriented approach, LCC focuses on all resources consumed by the investigated product or process system, during its lifetime. Through LCC, these resources are quantified as costs (Bagg, 2013), including the current costs related to the initial investment, operating, maintenance, replacement and disposal (Hin and Zmeureanu, 2014).

Three levels of assessments are essentially identified in the literature: conventional LCC (cLCC), environmental LCC (eLCC) and social LCC (sLCC). Conventional LCC (cLCC) can be defined as the sum of all funds expended for an item, from its conception and fabrication through its operation up to the end of its useful life (White and Ostwald, 1976). These funds are also referred to as *internal costs*. Environmental LCC (eLCC) expands cLCC, by including also the *external costs* of environmental impacts (also known as *externalities* or *environmental costs*) (Bierer et al., 2015). In particular, environmental externalities arise from climate change and from other changes in air or in water and soil quality, inducing impacts on human health, the developed environment and ecosystems (Stern, 2006). Social LCC (sLCC), in addition to the costs taken into account by cLCC and eLCC, assesses all costs associated with the life cycle of a product or service that are borne by anyone in the society (macro-economic level), whether today or in the future (Hunkeler et al., 2008).

Therefore, eLCC and sLCC are built-on and expand the scope and boundaries of cLCC, as shown in Figure 9.

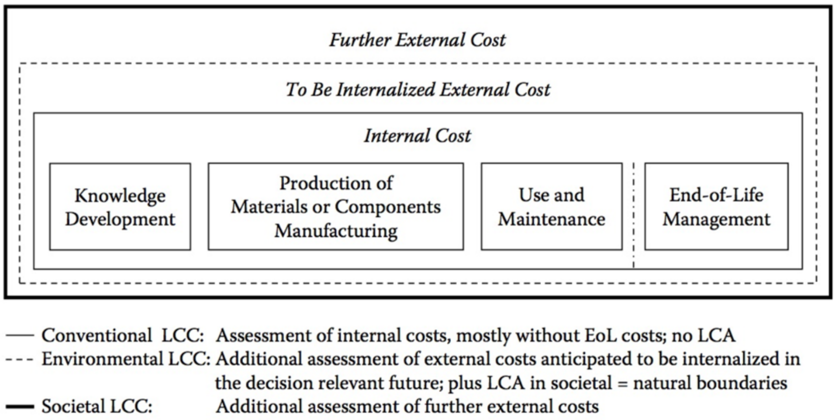

Figure 9 - Boundaries of conventional, environmental and social LCC.

In this study, the LCC was carried out, focusing on the economic costs of the environmental impacts (external costs). These results, combined with those from LCA, allow policymakers to get a deeper insight of the pros and cons of each investigated scenario. This knowledge is crucial for developing effective and sustainable biowaste management strategies.

3.1 Environmental Priority Strategies (EPS) methodology

According to a recently performed review (Amadei et al., 2021) there is a lack of consensus on LCC methods for the evaluation of the external costs (externalities), since these specific monetary evaluations vary across all impact categories and within each impact category, not providing a standardized approach. In this study, in line with recent scientific literature, the Environmental Priority Strategies (EPS) method (version 2015dx) was applied for the monetization of the externalities (Medina-Salgado et al., 2021). The EPS method follows the LCA methodology, according to the ISO standards 14040 and 14044 (2006). Impacts from emissions and use of resources, which cause significant changes in any of the Safeguard Subjects (i.e., areas of protection: Eco-system Services – ES-, Access to Water – AW -, Abiotic Resources – AR -, Human Health – HH - and BioDiversity – BD), are investigated.

The results of the EPS impact assessment method are monetary values (monetarization) of environmental impacts from emissions and use of resources. They are indicated as damage costs and are expressed as ELU (Environmental Load Units). One ELU represents an externality corresponding to 1 Euro of environmental damage cost. The cost or a "price" can be developed from individuals' "Willingness to pay (WTP)". In particular, WTP represents the value that an average OECD-inhabitant, having the impacts on her/himself, is willing to pay to avoid environmental damage (Rydh et al., 2002; Baumann and Tillman, 2004). Global average damage costs are estimated for emissions and resources, and the reference is the present state of environment (business as usual), in the year 2015.

Therefore, the basic idea of EPS is to make a list of environmental damage costs available to the analyst, in the same way as ordinary costs are available for materials, processes and parts. Damage costs for an emission or used resource are determined as the sum of damage costs they cause on each investigated safeguard subject, via different mechanisms (pathways).

3.2 **Goal and scope**

The objective of this LCC analysis was to provide local managers and politicians with information about the economic costs of the environmental impacts from the investigated scenarios.

These data are useful for gaining greater awareness of the consequences of different management strategies for biowaste from forestry and wood processing. Therefore, LCC results can effectively support decision-makers in developing appropriate policies to promote circular and sustainable biowaste management systems.

In order to allow for comparison with LCA results, the same system boundaries, assumptions, and functional unit, as in LCA analyses, were adopted for this LCC study.

3.3 External costs (externalities) of the PP pilot area

In Table 9, the environmental damage costs of the three investigated scenarios, for each safeguard subject, are reported. The percentage values are also displayed (Figure 10) in order to highlight the relative contribution of each scenario.

Table 9 - Comparison among the externalities of the BaU, Alternative Bioenergy and Alternative Biochemicals scenarios, referred to the selected FU (1 ton of residues from forestry and wood processing).

Safeguard subject	Unit*	BaU scenario	Alternative Bioenergy scenario-	Alternative Biochemicals scenario
Ecosystem services	ELU	-1,66E-02	-3,35E-01	-5,01E-01
Access to water	ELU	-3,99E-04	-2,03E-02	-2,83E-02
Biodiversity	ELU	5,40E-05	-1,00E-03	-1,49E-03
Human health	ELU	-2,83E-04	-2,85E-03	-4,01E-03
Abiotic resources	ELU	-1,18E-01	-1,45E+01	-3,40E+01
Total	**ELU**	**-7,23E+00**	**-3,93E+01**	**-1,66E+02**

**1 ELU: 1 Euro*

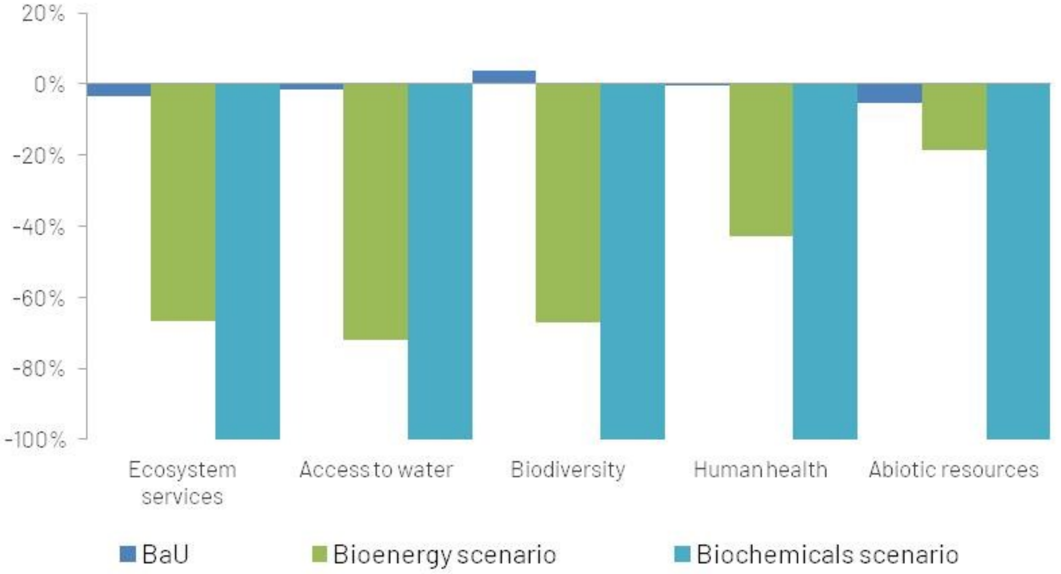

Figure 10 - Percentage contribution of BaU, Alternative Energy Valorization and Alternative Biochemicals scenarios to each safeguard subject.

The data in Table 9 show that all scenarios lead to a net saving of environmental damage costs. The highest contribution comes from the Biochemicals scenario (-1.66E-02 €/FU), followed by the Bioenergy one (-3.93E+01 €/FU). In particular, as shown in Figure 10, in all the investigated safeguard subjects, the greatest savings are always attributed to the Biochemicals scenario, while the Bioenergy scenario ranks second, with contributions ranging between 19%, in Abiotic resources, and 72%, in Access to water. Finally, the BaU scenario is the only one responsible for the environmental damage costs (5,40E-05 €/FU) in the biodiversity area of protection, while in the other safeguard subjects it contributes to save environmental damage costs, although in a much lesser extent than the alternative scenarios (Biochemicals and Bioenergy).

In order to understand which processes mainly contribute to the net externalities, below a deeper analysis of the three scenarios is reported.

The total environmental damage cost for BaU scenario (Table 10) amounts to about -7,23 €/FU, thus indicating a net (even if very small) saving in the environmental damage costs. The highest savings (-7,09 €/FU) are found for Abiotic resources. Human health ranks second and Ecosystem services ranks third with savings of -1.18E-01 €/FU and -1.66E-02 €/FU, respectively. These savings are mainly (53%) due to the avoided production of chemical N-fertilizers (-4,84 €/FU), followed by the avoided production of K-fertilizers (-2,67 €/FU) and P-fertilizers (-1,44 €/FU), which contribute to the total savings 30% and 16%, respectively. In particular, the avoided consumption of the N, K and P mineral resources brings savings to all the investigated safeguard subjects, ranging from -6,15E-05 €/FU, in Biodiversity, to -8,41 €/FU, in Abiotic resources.

Table 10 - Externalities of the BaU scenario, referred to the selected FU (1 ton of residues from forestry and wood processing).

Safeguard subject	Unit*	Total	Biomass left on the ground	Pellets	Compost	Avoided N Fertilizers	Avoided P Fertilizers	Avoided K Fertilizers
Ecosystem services	ELU	-1,66E-02	0,00E+00	4,57E-03	-5,86E-03	-8,98E-03	-1,68E-03	-4,60E-03
Access to water	ELU	-3,99E-04	0,00E+00	2,70E-04	3,30E-04	-5,94E-04	-1,04E-04	-3,00E-04
Biodiversity	ELU	5,40E-05	0,00E+00	1,50E-05	1,01E-04	-3,63E-05	-6,60E-06	-1,86E-05
Human health	ELU	-1,18E-01	0,00E+00	2,49E-01	2,58E-01	-3,59E-01	-6,93E-02	-1,96E-01
Abiotic resources	ELU	-7,09E+00	0,00E+00	4,11E-01	9,03E-01	-4,47E+00	-1,37E+00	-2,56E+00
Total	ELU	**-7,23E+00**	**0,00E+00**	**6,65E-01**	**1,16E+00**	**-4,84E+00**	**-1,44E+00**	**-2,76E+00**

**1 ELU: 1 Euro*

The composting process brings savings in environmental costs in Ecosystem services (-5.86E-03 €/FU), while in the other safeguard subjects it corresponds to expenses for environmental restoration. Finally, Pellet production determines environmental damage costs in all five examined protection areas, with values ranging from 1.50E-05 €/FU, in Biodiversity, to 4.11E-01 €/FU, in Abiotic resources.

Table 11 shows that the processes most responsible for the costs of environmental damage in the Biochemicals scenario are the production of bio-BDO (49%) and bio-SA (38%). Ethyl levulinate production ranks third (11%), while the residual biomass valorization as compost and pellets has a much lower impact, contributing 2% and 1%, respectively. Finally, the damage cost of transport is negligible (<1%).

Table 11 - Externalities of the alternative Biochemicals scenario, referred to the selected FU (1 ton of residues from forestry and wood processing).

Safeguard subject	Unit*	Total	Pellet	Compost	Biochemicals - Ethyl levulinate	Biochemicals - BDO	Biochemicals - SA	Transport	Avoided Fertilizers (N, K, P)	Avoided fossil SA	Avoided fossil BDO	Avoided fossil Ethyl levulinate
Ecosystem services	ELU	-5,01E-01	4,57E-03	-5,86E-03	5,17E-02	3,04E-01	4,83E-02	3,66E-04	-1,53E-02	-9,39E-02	-6,91E-01	-1,04E-01
Access to water	ELU	-2,83E-02	2,70E-04	3,30E-04	3,11E-03	1,85E-02	2,88E-03	2,14E-05	-9,98E-04	-5,71E-03	-4,08E-02	-5,96E-03
Biodiversity	ELU	-1,49E-03	1,50E-05	1,01E-04	1,68E-04	9,71E-04	1,60E-04	1,19E-06	-6,15E-05	-3,08E-04	-2,21E-03	-3,35E-04
Human health	ELU	-3,40E+01	2,49E-01	2,58E-01	2,58E+00	1,14E+01	2,42E+00	1,76E-02	-6,25E-01	-4,56E+00	-4,02E+01	-5,59E+00
Abiotic resources	ELU	-1,31E+02	4,11E-01	9,03E-01	5,53E+00	2,52E+01	2,62E+01	4,11E-02	-8,41E+00	-2,08E+01	-1,34E+02	-2,60E+01
Total	**ELU**	**-1,66E+02**	**6,65E-01**	**1,16E+00**	**8,16E+00**	**3,70E+01**	**2,87E+01**	**5,91E-02**	**-9,05E+00**	**-2,55E+01**	**-1,75E+02**	**-3,17E+01**

**1 ELU: 1 Euro*

In all safeguard subjects, the Avoided fossil BDO determines the greatest savings (73% of the total), leading to an overall avoided cost of -1.75E+02 €/FU (Table 11). The second and the third highest contributors, in terms of cost savings related to environmental damage, are the Avoided production of fossil Ethyl levulinate (-3.17E+01 €/FU, 13% of the total) and the Avoided production of fossil Succinic acid (-2.55E+01 €/FU, 11% of the total), respectively. Another process that results in a slight cost saving (-9.05E+00 €/FU, 4% of the total) is the avoided production of chemical fertilizers (N, P, K). All these processes determine a saving of mineral and fossil resources and, consequently, it is not surprising that the area of protection for which the greatest savings are recorded (-1.31E+02 €/FU) is Abiotic resources. Another significant saving is achieved in the Human Health (-3.40E+01 €/FU) area of protection. For the other safeguard subjects, the environmental damage costs and savings are negligible (Table 11).

In Table 12, the externalities of the alternative Bioenergy scenario, for each area of protection, are reported. In all the investigated areas, a net saving of environmental damage costs is achieved. The safeguard subject that accounts for the majority of savings (62%) is, once again, Abiotic resources (-2.44E+01 €/FU), followed by Human health (37%) which allows to avoid 1.45E +01€/FU of environmental remediation costs. Savings for Ecosystem services represent 1% of the total, while the savings observed in Access to water and Biodiversity safeguard subjects are even lower (<1%). The savings for Abiotic resources derive mainly from the avoided consumption of electricity (41%), followed by the avoided production of chemical fertilizers (31%) and the avoided extraction of natural gas (28%). CHP process contributes for 53% to the environmental damage costs, while composting and pelletizing are responsible for 32% and 15%, respectively, and transport represents only 1%. Regarding the safeguard subject Human health, 92% of the environmental damage costs are attributable to the CHP process, while both palletization and composting are responsible for 4% of expenditures. Even in this case, the cost associated with damage from transport, is negligible (-1.76E-02 €/FU). Furthermore, the overall savings for Human health amount to -2.13E+01€/FU, to which the avoided production of: (i) natural gas, (ii) electricity and (iii) inorganic fertilizers (N, K and P) contribute for 56%, 41% and 3%, respectively. For the other areas of protection, savings and environmental damage costs are not significant (Table 12).

Table 12- Externalities of the Alternative Bioenergy scenario, referred to the selected FU (1 ton of residues from forestry and wood processing).

Safeguard subjects	Unit*	Total Bioenergy scenario	Pellets	Compost	CHP process	Transport	Avoided Fertilisers (N, P, K)	Avoided Electricity, medium voltage	Avoided natural gas
Ecosystem services	ELU	-3,35E-01	4,57E-03	-5,86E-03	-5,81E-03	3,66E-04	-1,53E-02	-1,65E-01	-1,47E-01
Access to water	ELU	-2,03E-02	2,70E-04	3,30E-04	-1,44E-03	2,14E-05	-9,98E-04	-1,01E-02	-8,38E-03
Biodiversity	ELU	-1,00E-03	1,50E-05	1,01E-04	-1,99E-05	1,19E-06	-6,15E-05	-5,47E-04	-4,91E-04
Human health	ELU	-1,45E+01	2,49E-01	2,58E-01	6,31E+00	1,76E-02	-6,25E-01	-8,75E+00	-1,20E+01
Abiotic resources	ELU	-2,44E+01	4,11E-01	9,03E-01	1,51E+00	4,11E-02	-8,41E+00	-1,13E+01	-7,59E+00
Total	**ELU**	**-3,93E+01**	**6,65E-01**	**1,16E+00**	**7,82E+00**	**5,91E-02**	**-9,05E+00**	**-2,02E+01**	**-1,97E+01**

**1 ELU: 1 Euro*

4. CONCLUSIONS

The LCA/LCC studies, for the PP pilot area, assessed the potential environmental loads and benefits and their related economic costs for the current biowaste management scenarios (BaU) and the Alternative valorization scenarios. As a general result, it turned out that the benefits coming from the substitution of fossil products with bio-counterparts overcome the environmental damages deriving from the bio-products production processes. However, it should be noted that the analyses were based on several hypotheses, due to the lack of numerous primary data. Consequently, the results are not as reliable as if only primary data were used.

In light of the findings, the following conclusions have been drawn for the analyzed biowaste chain.

- The Biochemicals scenario results to be the most sustainable for managing the residual biomass, thanks to the benefits associated with the production of bio-based chemicals.
- The greatest environmental advantages come from the avoided production of fossil BDO.
- The Bioenergy scenario leads to greater environmental advantages than the Biochemicals scenario only in the EF impact category, but much higher loads in ET impact category.
- The highest impact (hotspot), in both alternative scenarios, is due to electricity consumption in the production phase (biorefinery or CHP plant). Therefore, an increased use of renewable energy and/or of low energy consumption for machinery (by using the Best Available Technologies) is advisable.
- The valorization of an additional 25% of residual biomass, through its conversion into biochemical products (Alternative scenario - Biochemicals), could bring economic benefits, due to savings in environmental remediation costs. However, the collection of this further percentage of residual biomass depends on logistical feasibility. This is also highlighted in the Bulgarian FSC certification standard (Indicator 10.11.4) (https://connect.fsc.org/document-centre/documents/resource/21). A slope of 20-22°, as commonly observed in Bulgaria, is considered the operational limit for rubber-wheeled harvesters and forwarders. However, this limit can be substantially extended with cable-assist systems (Visser and Stampfer, 2015).
- For the PP pilot area, Alterative scenarios should be designed with a more conservative approach (e.g. leaving about 15% of forestry residues on the ground) for a better residues management, in order to safeguard the forestry ecosystem. The valorization of an additional 10% of forestry residues, compared to the current management scenario, allows to reduce/prevent frequent open fires as well.

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