

Article

Solid Pellet Biofuel Made from Coffee Grounds: Experimental and Environmental Analysis

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Abstract

Spent coffee grounds (SCGs) are a waste product generated in large volumes worldwide, given that coffee is the second most consumed beverage on the planet. Although it typically ends up in landfills, this biomass contains a high amount of nutrients, organic compounds, and other physical properties that can be harnessed. It is possible to recover energy from coffee grounds through pellet production because this biomass has a calorific value ranging from 19.6 to 21.1 MJ/kg—values comparable to, and even higher than, those of traditional fuel biomasses, such as pine sawdust (18.64 MJ/kg) or eucalyptus wood (17.38 MJ/kg). To produce the pellets, different formulations were prepared by incorporating up to 25% SCGs and up to 80% recycled woody material, depending on the specific formulation, followed by the addition of the 5% additive. All proportions were expressed as percentages of the total biomass mixture mass. The resulting pellets were characterized in accordance with ISO 17225-1 and have been classified as Type B non-woody pellets. Given that bioenergy derived from waste plays a fundamental role in climate change mitigation and the circular economy, a cradle-to-gate life cycle assessment was conducted using the ReCiPe 2016 Endpoint method. The results revealed that the pellets containing SCGs were more environmentally friendly.

Keywords: spent coffee grounds; solid pellet biofuel; biomass pellets; life cycle assessment; cradle-to-gate; waste valorization



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1. Introduction

The growing global demand for sustainable energy has driven the search for alternatives capable of mitigating the environmental impacts associated with fossil fuels. Among these alternatives, solid biofuels have emerged as a particularly attractive option due to their renewable nature and the availability of lignocellulosic feedstocks and organic waste. In this context, biomass pellets have established themselves as one of the most widely used solid biofuels worldwide, with global wood pellets consumption reaching 45 million metric tons in 2024 [1]. Their widespread use is mainly attributed to their high energy density, ease of transport, compositional uniformity, and compatibility with both domestic and industrial combustion systems [2]. However, large-scale pellet production requires the assurance of environmental sustainability, a stable supply of raw materials, and compliance

with international standards such as the ISO 17225-1 series, which provides clear and unambiguous classification principles for solid biofuel [3].

An emerging strategy in the field of solid biofuels involves the valorization of organic waste generated by the agricultural and food industries. This approach promotes the circular economy by reintegrating waste into energy production chains, reducing pressure on forest resources, and preventing inappropriate disposal. Accordingly, a wide range of agricultural and agro-industrial residues, including wheat straw, rye, barley, rapeseed straw, grasses in general (hay), olive pomace, grape pomace, olive pits, cotton stalks and residues, and Pennsylvania mallow, as well as pits and shells from fruits including rice, sunflower, apricot, peach, cherries, almonds, hazelnuts, pine nuts, and oil palm shells, have been investigated, with their characterization included in Annex B of the ISO 17225-1 standard [3].

Among the organic waste generated by the food industry with potential for energy recovery but not yet specifically categorized are spent coffee grounds (SCGs), which are produced in large volumes worldwide. During the most recent coffee year (2023–2024), 11.39 million metric tons of SCGs were produced [4], and are classified by the European Waste List (EWL) under code 020399 [5]. Their carbon content, exceeding 46.52% [6], lignin content ranging between 20% and 25% [7], relatively high calorific value of approximately 18.8 to 25.2 MJ/kg [8], and continuous availability make SCGs a promising feedstock for the production of solid biofuels. Evidence of the energy potential of this waste is provided by its industrial implementation at the JDE Peet plant (Netherlands)—a global leader in the coffee and tea sector. At this facility, biomass boilers fueled by coffee grounds are used to replace natural gas for the generation of steam required in the production process [9]. In Girona (Spain), the multinational company Nestlé—whose factory is a leader in the production of instant coffee and single-serve capsule beverages—has commissioned a second steam boiler. This facility enables the recovery of 100% of the coffee grounds generated during the production process, thereby closing the waste cycle within the same industrial plant [10]. Similarly, the British company Bio-bean—a pioneer in the United Kingdom in the recycling of coffee grounds on an industrial scale—has developed processes for converting this waste into briquettes and other high-efficiency biofuels, demonstrating the feasibility of transforming waste generated by urban coffee shops into renewable energy resources [11].

In recent years, various studies have demonstrated the potential of SCGs as a biofuel in the form of briquettes [12–17] or pellets [18–32]. Nevertheless, challenges remain regarding its density, mechanical durability, thermal stability, and emissions during combustion. These limitations often require the co-pelletization of SCGs with other lignocellulosic materials, such as pine sawdust [23,27], spruce sawdust [26], or any type of sawmill waste [19]. Similarly, other residues from the coffee-processing industry, such as coffee husks [19] and coffee silverskin [18], have been investigated. In addition, other agricultural residues, such as red pepper stems [27] and agro-industrial residues, including spent tea grounds [20], orange juice waste [28] or brewery spent grain [33] have been utilized. However, since wood remains the benchmark feedstock due to its excellent mechanical properties and combustion stability, its blending with SCGs is emerging as a promising strategy for producing a solid biofuel capable of meeting the required quality standards.

Given the complexity of these biofuels systems, the scientific community has shown increasing interest in the comprehensive assessment of their environmental impacts. Although solid biofuels are considered to have a relatively low environmental footprint, their production involves energy consumption and associated environmental burdens that must be rigorously quantified. In this regard, Life Cycle Assessment (LCA) has established itself as a reference methodology for this type of evaluation [34]. Through the systematic modeling and quantification of environmental burdens associated with the different stages

of the production system—LCA enables the identification of environmental hotspots and supports the optimization of the overall sustainability performance of the system [35,36].

Over the past decade, several studies have applied LCA to solid biofuels, reporting heterogeneous results depending on the feedstock employed, drying conditions, energy requirements associated with pelletization, and transportation distances [37–39]. Although there is general agreement that wood pellets exhibit a favorable environmental performance, available evidence suggests that the incorporation of organic waste streams may further improve their environmental profile [40]. However, scientific debate remains regarding the environmental implications of biomass utilization. While some authors question whether the carbon neutrality of biomass is potentially overestimated, others emphasize relevant indirect environmental benefits, including the diversion of waste from landfills and the recovery and valorization of secondary raw materials [41].

Within this context, the use of coffee grounds (SCGs) as an energy feedstock represents an underutilized opportunity whose environmental performance has not yet been sufficiently documented. To address this research gap, the present study investigates the use of SCGs in combination with recovered woody biomass. Specifically, woody material containing 80% recycled content was used, sourced from the circular economy system of Sonae Arauco España-Soluciones de Madera, S.L. (Linares, Jaén, Spain), thereby contributing to the extension of the period of CO₂ sequestration in wood-based materials. The remaining 20% consists of poplar (*Populus nigra*) and pine (*Pinus pinaster*) wood certified under the FSC® and PEFC responsible forest management standards [42,43]. Therefore, it is essential to determine whether this specific combination of coffee and recovered wood is both technically and environmentally viable. The hypothesis is that SCGs can be incorporated at up to 25 per cent into mixtures containing woody material for pellet production without compromising compliance with the applicable quality requirements, while achieving a competitive environmental performance profile.

To test this hypothesis, the present research adopts a two-pronged approach. First, the blends were experimentally optimized to achieve compliance with the ISO 17225-1 standard [3], considering key quality parameters such as calorific value, mechanical durability, and the potential emissions associated with N, S, and Cl. Second, a comprehensive LCA was conducted using SimaPro software. This integrated approach enables the quantification of the environmental impacts associated with the production system, the identification of the processes contributing most significantly to the overall environmental footprint, and a direct comparison with conventional wood pellets. Consequently, the study provides a comprehensive and reproducible assessment of the technical and environmental performance of SCG-based pellets and contributes to the evaluation of their potential for industrial-scale energy valorization [44,45].

2. Materials and Methods

2.1. Biofuel Components

2.1.1. Spent Coffee Grounds

The waste material was obtained through a selective collection system at the generating establishments, following a local circular economy model (Km 0). This local supply strategy minimizes the environmental impacts associated with transportation, which is a key factor in Life Cycle Analysis. The waste, with an initial average moisture content of 60.06%, was stabilized by thermal drying at 105 °C for 24 h until a final average moisture content of 9.96% was achieved. For biofuel production, the particle size fraction ranging from 0.5 to 1.0 mm was selected, following the recommendation of the pelletizer manufacturer [46] and in agreement with the particle size ranges reported by other researchers: 0.5–1.0 mm [26] and 0.5–0.9 mm [31].

2.1.2. Wood Particles

The lignocellulosic base material was supplied by a local particleboard manufacturing facility. Eighty percent of the raw material consisted of recycled wood supplied by Tecnologías del Medio Ambiente S.A. (Tecnasa, Madrid, Spain). This material was sourced from various collection and processing centers throughout the Iberian Peninsula, with an average transportation distance of 239.65 km to the industrial plant. The remaining 20% consisted of woody biomass from sustainably managed pine (*Pinus pinaster*) and black poplar (*Populus nigra*) plantations; these forests are located within an average radius of 250 km from the manufacturing plants. The wood particles had a particle size ranging from 0.63 to 12.0 mm, as determined using an IRIS FTL-0200 digital electromagnetic sieve shaker (FILTRA VIBRACION, S.L., Badalona, Spain) and a set of standard sieves in accordance with ISO 3310-1 [47]. The moisture content was approximately 5%, as determined by mass difference after drying the samples in a Memmert UF260 oven (Mettler GmbH + Co. KG, Schwabach, Germany) at 105 °C for 24 h [48].

2.1.3. Additives

In accordance with ISO 17225-1 [3], which permits the use of additives (up to 20% by mass) to improve pellet consistency, handling, or combustion performance, cornstarch was incorporated as an additive. Its use is supported both by the standard (Table 4 of ISO 17225-1 [3]) and by previous studies on biomass densification in which this additive has been employed [18,49–51]. Additives can improve pellet durability, facilitate the densification process and, when the electricity used for densification is generated from fossil fuels, contribute to mitigating greenhouse gas emissions [52]. To reinforce the local nature of the study, this binding agent was purchased from a local supplier.

The physicochemical characteristics of the raw materials used are summarized in Table 1. The higher heating value (HHV) and lower heating value (LHV) were determined using a Parr 1108 oxygen combustion bomb calibrated with certified benzoic acid, in accordance with ISO 18125 [53]. Moisture content was determined according to ISO 18134-2 [48]. Ash content was determined from the mass of the residue remaining after the sample was heated under controlled conditions to a final temperature of 550 ± 10 °C in a TecnoPiro B5-S furnace (TecnoPiro, Barcelona, Spain), in accordance with the procedure specified in ISO 18122 [54]. Carbohydrate and lignin content were determined according to the methodology established by Browning [55], via high-performance liquid chromatography (HPLC) with a WATERS system under the following conditions: a BIO-RAD Aminex HPX-87H column (300 mm $\times$ 7.8 mm) maintained at 45 °C, sulfuric acid (0.49 kg/m³) as the mobile phase, a flow rate of 0.6 cm³/min, a refractive index (RI) detector, and a sample injection volume of 20 μ L [56]. Nitrogen, carbon, and hydrogen contents were determined simultaneously using the total combustion technique with the LECO TruSpec MACRO CHN Elemental Analyzer (LECO Corporation, St. Joseph, MI, USA). Sulfur and chlorine contents were determined using combustion followed by the ion chromatography method, as specified in ISO 16994 [57].

To evaluate the effect of incorporating coffee grounds into recycled wood-based material, five experimental formulations were designed to cover a representative range, allowing the identification of the technical limit for SCGs incorporation without compromising compliance with the quality requirements of ISO 17225-1 [3]. In all formulations, the addition of 5% cornstarch was kept constant, corresponding to the maximum permissible concentration for non-wood pellets according to ISO 17225-6 [58]. The additive acts as a binding agent to promote uniformity during the pelletization process.

Table 2 presents the proposed mixtures and the corresponding mass fractions of the main raw materials. To facilitate the identification and comparison of the results, a nomen-

clature based on SCGs content was adopted. For example, sample W10 refers to pellets composed of a 10% SCGs and 90% wood mixture, based on the biomass fraction, while maintaining the aforementioned additive at a constant proportion of the total formulation.

Table 1. Physicochemical characteristics of the raw materials.

Raw Material	HHV [MJ/kg]	LHV [MJ/kg]	Moisture [%] *	Ash [%] *	Lignin [%]	Hemicellulose [%]	Cellulose [%]	N [%]	C [%]	H [%]	S [%]	Cl [%]
SCGs	21.140 ± 0.006	19.609 ± 0.006	6.648 ± 0.217	1.241 ± 0.019	33.600 ± 0.420	43.160 ± 1.000	7.630 ± 0.130	2.245	49.705	6.596	0.101	0.015
Wood	18.023 ± 0.330	16.698 ± 0.330	7.594 ± 0.524	4.350 ± 0.263	31.410 ± 0.710	18.990 ± 0.750	34.600 ± 0.260	1.969	46.550	5.576	0.061	0.112
Cornstarch	16.950 ± 0.418	16.661 ± 0.418	13.178 ± 0.355	0.079 ± 0.0008	-	-	-	0.057	40.488	6.465	0.018	0.050

* Mass dry basis.

Table 2. Relative concentrations of coffee grounds and wood in the different mixtures studied.

Nomenclature	W00	W05	W10	W15	W20	W25
SCGs [%]	0	5	10	15	20	25
Wood [%]	100	95	90	85	80	75

2.2. Pellet Production

The pelletization process is defined as the agglomeration of biomass into larger, cylindrical particles, or pellets, through the application of mechanical forces, pressure, heat, and moisture [59]. In this study, the formulations were conditioned through a moistening stage during the 24 h prior to processing, adjusting the moisture content to 14%, as recommended by the manufacturer of the unheated Ceccato Olindo Mod (Ceccato Olindo S.r.l., Padova, Italy). 7.5 HP pelletizer used [46]. Particulate material was fed in every 50 s, and the densified pellets exited the die at an average temperature of 62.95 °C as a result of mechanical friction.

After production, the pellets were subjected to a stabilization period of approximately 10 days under controlled conditions—35% relative humidity and a room temperature of 20 °C—to ensure hygroscopic equilibrium before their characterization.

2.3. Characterization of Pellets

The characterization of the biofuels was performed according to the criteria established in ISO 17225-1 [3], as shown in Table 3. The evaluation included an assessment of the physical, mechanical, and chemical properties. During samples preparation, the protocol established in ISO 14780 [60] was followed.

Table 3. Evaluated properties of pellet-type solid biofuel, in accordance with the requirements of ISO 17225-1 [3].

Property	Abbreviation	Comments
Diameter and Length	D, L	ISO 17829 [61]
Moisture content	M	ISO 18134-2 [48] % of mass as received
Ash	A	ISO 18122 [54] % of mass on dry basis
Mechanical durability	DU	ISO 17831-1 [62] % of mass of pellets after testing

Table 3. *Cont.*

Property	Abbreviation	Comments
Amount of fines	F	ISO 5370 [63] % of mass, <3.15 mm
Net calorific value	Q	ISO 18125 [53] MJ/kg as received
Bulk density	BD	ISO 17828 [64] kg/m ³ as received
Nitrogen	N	ISO 16948 [65] % of mass on dry basis
Sulfur	S	ISO 16994 [57] % of mass on dry basis
Chlorine	Cl	ISO 16994 [57] % of mass on dry basis
Carbon	C	ISO 16948 [65] % of mass on dry basis
Volatile matter	VM	ISO 18123 [66] % of mass on dry basis

2.4. Life Cycle Assessment

Life cycle assessment (LCA) is a standardized and globally recognized methodology for assessing the environmental impacts of any production system throughout all its stages, following the guidelines of the ISO 14040 standard [67]. In this research, it is applied to comprehensively analyze the supply chain, manufacturing, and potential use of the developed pellets. This approach allows the identification of critical points (hotspots) in the process that require improvement and provides a transparent technical basis for optimizing the energy utilization of biomass under sustainability criteria.

2.4.1. Objective and Scope of the Study

To ensure the consistency of the analysis and the comparability of the results, commercial pellets were not used as a reference. Instead, a control sample (W00) was manufactured, consisting exclusively of the same wood matrix (80% recycled and 20% virgin), and the additive used in the SCG-containing mixtures. This methodological approach allows the environmental effect of incorporating SCGs to be isolated, while eliminating external variables such as differences in the origin of the woody biomass or large-scale industrial manufacturing processes.

The scope of this study encompasses the stages from the collection and processing of the biomass feedstocks to the production of the pellets.

2.4.2. Functional Unit and System Boundaries

The functional unit (FU) was defined as 1 t of manufactured pellets for the environmental assessment, and this is a commonly used unit of measurement in this type of study. The energy and mass flows used to develop the life cycle inventory (LCI) were analyzed on the basis of 1 kg of materials.

Regarding the system boundaries, a “cradle-to-gate” approach was adopted (see Figure 1). This approach includes the procurement and preliminary processing of raw materials, as well as the mechanical densification stage using the 7.5 HP pelletizer, with the system ending at the factory’s exit gate once the production process has been completed. Given this scope, neither the end-use stage (combustion) nor ash disposal was considered;

the assessment focuses exclusively on the environmental impacts associated with pellet production.

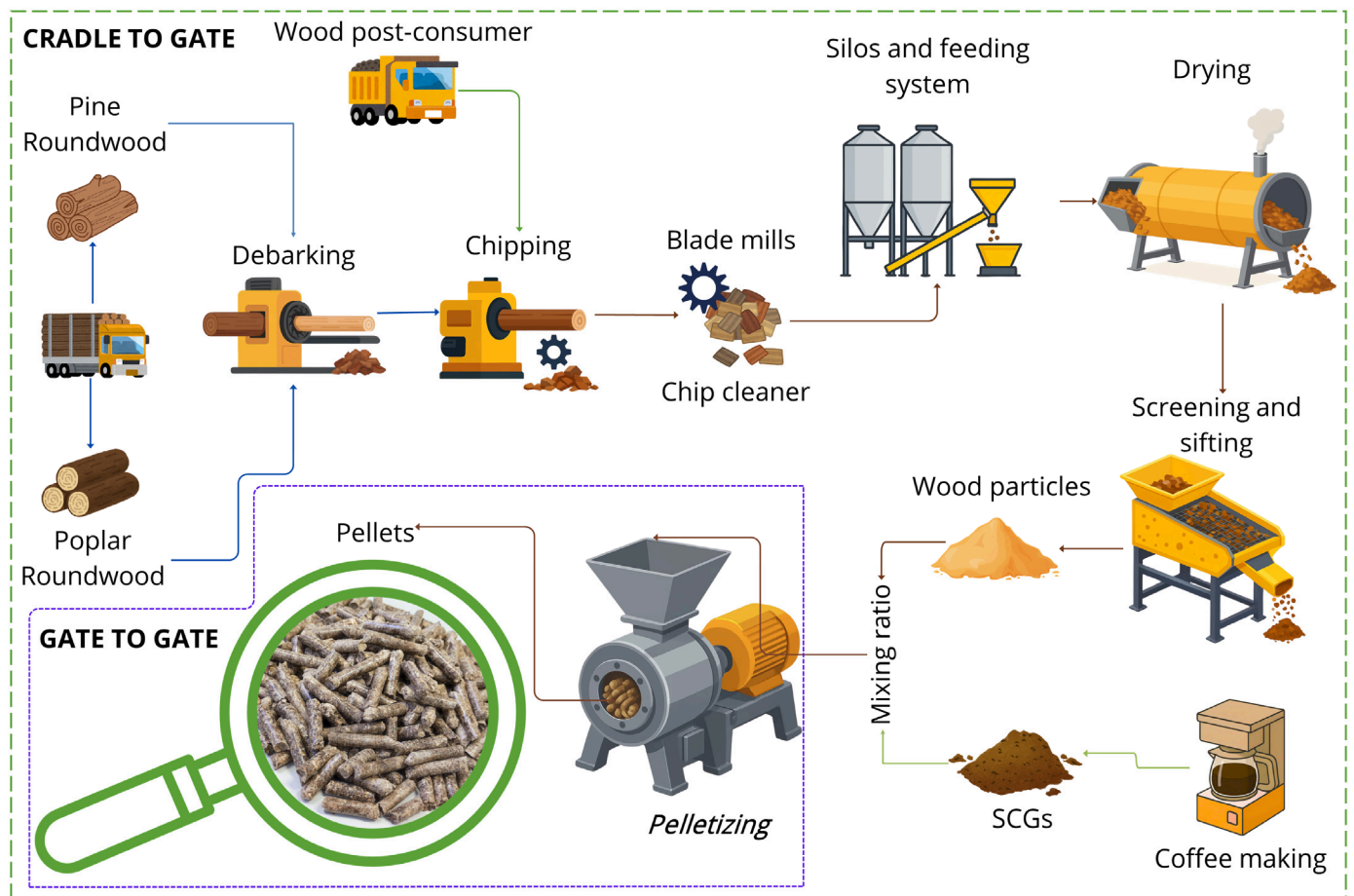


Figure 1. Diagram of the system boundary for the life cycle of SCGs pellet production.

The study focuses on an internal comparison of formulations developed under the same experimental conditions. Since the wood used has a lower environmental footprint due to its recycled origin (Sonae Arauco, Mangualde, Portugal), a comparison with commercial pellets produced exclusively from virgin wood would be asymmetrical and would not allow for an accurate quantification of the net environmental impact associated with replacing wood with SCGs.

2.4.3. Impact Categories and Impact Assessment Methods

The environmental impact assessment was conducted using the ReCiPe 2016 Endpoint (H) V1.03/World (2010) H/A global method, in accordance with the guidelines of ISO 14044 [68]. This method incorporates twenty-two impact indicators grouped into three endpoint damage categories: human health, ecosystem quality, and resource scarcity (Table 4). The results were expressed in ecopoints (Pt), which provide an integrated representation of tradeoffs among the different categories and facilitate the interpretation of results for decision-making.

An Endpoint approach was selected due to its ability to aggregate the complexity of midpoint indicators into single scores, providing a transparent basis for comparing the different formulations [69–71]. Although this level of aggregation involves greater uncertainty than Midpoint indicators [72], the experimental design adopted in this study—comprising five formulations under identical conditions—provides an intrinsic sensitivity analysis. The consistency of the trends observed across the biomass substitution gradient strengthens

the reliability of the conclusions, indicating that the observed environmental benefits are primarily associated with the proposed circular economy model rather than with minor variations in the life cycle inventory data.

Table 4. Impacts considered for damage assessment.

Damage Category	Impact Category	Unit
Human health	Global warming, Human health	Daly
	Stratospheric ozone depletion	
	Ionizing radiation	
	Ozone formation, Human health	
	Fine particulate matter formation	
	Human carcinogenic toxicity	
	Human non-carcinogenic toxicity	
Ecosystems	Water consumption, Human health	Species.yr
	Global warming, Terrestrial ecosystems	
	Global warming, Freshwater ecosystems	
	Ozone formation, Terrestrial ecosystems	
	Terrestrial acidification	
	Freshwater eutrophication	
	Marine eutrophication	
	Terrestrial ecotoxicity	
	Freshwater ecotoxicity	
	Marine ecotoxicity	
	Land use	
Resources	Water consumption, Terrestrial ecosystems	USD2013
	Water consumption, Aquatic ecosystems	
	Mineral resource scarcity	
	Fossil resource scarcity	

Endpoint results provide a more integrated and readily interpretable representation of trade-offs among impact categories, which is advantageous for comparative assessment and policy-oriented interpretation, despite the greater uncertainty associated with endpoint indicators compared with midpoint indicators. The impact assessment method used in this study was chosen based on the scientific literature recommending its application when a comprehensive yet simplified assessment of environmental impacts is required, through the aggregation of impact indicators into three endpoint damage categories [70,71,73–75].

Furthermore, to assess the specific impact of critical stages in the solid biofuel production process—such as the transportation of raw materials using fossil-fuels-based system and electricity consumption during densification—and to perform a sensitivity analysis, the IPCC 2013 GWP 100a (v.1.03) method was used as a comparative benchmark. This method quantifies the Global Warming Potential (GWP) associated with greenhouse gas emissions using a single impact category, expressed as kg CO₂ eq over a 100-year time horizon [76].

Based on the optimal formulation selected according to the physical, mechanical and energy properties of the pellets, the sensitivity analysis considered three critical scenarios:

- (a) Scenario 1. The maximum transportation distance for which the net environmental benefit associated with the use of SCGs remains viable was determined. Since SCGs are highly dispersed across urban environments, its industrial-scale utilization requires a dedicated collection system. Therefore, the maximum permissible transportation distance was defined as the distance at which the total environmental impact of the optimal formulation becomes equal to that of the reference formulation (W00), according to the ReCiPe 2016 method.

- (b) Scenario 2. The effect of a 10% increase in electricity consumption during the pelletization process on the net environmental benefit was assessed, considering the Spanish national electricity grid as the geographical context.
- (c) Scenario 3. This scenario combines the transportation requirements associated with the collection of SCGs with a 10% increase in electricity consumption during the pelletization process.

2.4.4. Life Cycle Inventory

The SimaPro software (v.9.0.0.35) was used to develop the life cycle inventory, employing the Ecoinvent 3 database under the “Allocation, cut-off by classification” system model, which is based on the principle that the primary production of materials is always assigned to the primary user of a material [77]. Consequently, since SCGs are a waste product and the wood used is predominantly recycled, both materials enter the system “burden-free,” with only the impacts associated with their collection and subsequent processing being considered.

It is well established that the accuracy of an LCA depends directly on the quality of the Life Cycle Inventory (LCI) data [78]. Therefore, to minimize uncertainty, data corresponding to the raw material preparation and densification subsystems (Tables 5–9) were obtained through direct on-site measurements during the experimental trials. For secondary processes or generic inputs (such as electricity or cornstarch), data from the Ecoinvent database adapted to the geographic context of the study were used.

In addition, several considerations specific to the life cycle inventory should be noted. First, the bark removed from virgin wood logs was treated as a by-product in the simulation, as it is used for energy generation in the boiler of the mill supplying the material. Regarding emissions data, publicly reported values from the resolution issued by the Regional Ministry of Sustainability and the Environment (2024), corresponding to the review of the Integrated Environmental Authorization for the Sonae Arauco plant, were used to characterize wood processing [79]. The use of local administrative data improves the accuracy of the inventory compared to generic data from databases. For minor inputs, cornstarch was modeled assuming local transportation over a distance of 0.6 km by light vehicle. Finally, during the densification and stabilization stages, moisture losses were accounted for, assuming water vapour release to the environment until the product reaches its equilibrium state (moisture content $\leq 8\%$), thereby ensuring a complete mass balance in the system.

Table 5. Processing of 1 kg of wood chips: 50% pine and 50% poplar.

Inputs				
From Technosphere	Materials	Pine roundwood	0.00111	m ³
		Poplar roundwood	0.001086	m ³
	Energy	Debarking	0.0048	kWh
		Chipping	0.00875	kWh
		Blade mills	0.033333333	kWh
		Chip cleaner	0.000450549	kWh
		Total	0.047333883	kWh
	Transport	Transport of logs (16–32-tonne lorry)	250.00	km
Outputs				
To Technosphere	Materials	Virgin wood chips	1.00	kg
	Waste	Logs bark	0.20	kg
To Environment	Emissions to air	Airborne particles	0.005	mg

Table 6. Processing of 1 kg of recycled wood chips and shavings.

Inputs				
From Technosphere	Materials	Post-consumer wood	1.00	kg
		Chipping (hammers)	0.0331875	kWh
	Energy	Blade mills	0.018529412	kWh
		Chip cleaner	0.000450549	kWh
		Total	0.051716912	kWh
	Transport	Transport of post-consumer wood (16–32-tonne lorry)	239.65	km
Outputs				
To Technosphere	Materials	Recycled wood chips and shavings	1.00	kg
To Environment	Emissions to air	Particles in the air	0.004	mg

Table 7. Processing of 1 kg of wood consisting of 20% virgin wood chips and 80% recycled wood chips and shavings.

Inputs				
From Technosphere	Materials	Virgin wood chips	0.2115	kg
		Recycled wood chips and shavings	0.8255	kg
	Energy	Silos and feeding system	0.000177263	kWh
		Rotary dryer (Moisture 1.8%)	0.8252	kWh
		Screening and sifting	0.001093092	kWh
		Total	0.826470355	kWh
	Transport	Transport Sonae-UJA (medium-sized gasoline car)	10.3	km
Outputs				
To Technosphere	Materials	Wood particles	1.00	kg
To Environment	Emissions to air	Particles in the air	0.002	mg
		NO ₂	0.16	mg
		CO ₂	0.18	mg
		Water vapour	0.695	kg

Table 8. Processing of 1 kg of SCGs.

Inputs				
From Technosphere	Materials	SCGs wet	6.66	kg
		Oven drying	0.5438	kWh
	Energy	Sifting (particles > 0.5 mm)	0.132	kWh
		Total	0.6758	kWh
	Transport	Transport and collection	0.00	km
Outputs				
To Technosphere	Materials	SCGs	1.00	kg
To Environment	Waste	Particles	0.333	kg
	Emissions to air	Water vapour	5.300816	kg

Table 9. Processing of 1 kg of pellets from the different mixtures studied.

Outputs to Technosphere	Inputs from Technosphere				
	Wood [g]	SCGs [g]	Cornstarch [g]	Water [mL]	Pelletizing Energy [kWh]
W00	1000	0	50	81.49	0.0822820
W05	950	50	50	81.61	0.0822907
W10	900	100	50	82.66	0.0823670
W15	850	150	50	83.255	0.0824103
W20	800	200	50	83.84	0.0824528
W25	750	250	50	84.43	0.0824957

3. Results and Discussion

Figure 2 summarizes the regulatory framework used in this study to produce a sustainable pellet-type solid biofuel.

		ISO Standards	Scope	Biomass or Product	Main Objectives
Material Assessment		ISO 17225-1 (2021)	Fuel specifications and classes		Sources and types of solid biofuels.
		ISO 17225-2 (2021)	Wood pellets		For residential and industrial use.
		ISO 17225-6 (2021)	Non-woody pellets		The quality of non-wood pellets
		ISO 14780 (2017)	Sample preparation		Protocol for sample preparation and collection
Environmental Assessment		ISO 14040/14044 (2006)	Life Cycle Analysis		Environmental impacts assessment

Figure 2. ISO regulatory summary for solid pellet-type biofuels [3,58,60,67,68,80].

3.1. Physical, Mechanical, and Energetic Properties of the Pellets

Table 10 shows physicochemical properties obtained for each of the mixtures densified as solid pellet-type biofuel. The characterization was performed in accordance with ISO 17225-1 [3], as described in Section 2.3. The analysis allows the effect of the progressive incorporation of SCGs, ranging from 0% to 25% while maintaining a constant 5% cornstarch content, on the properties of the final product to be assessed. SCGs are an agro-industrial waste with high energy potential. However, their incorporation into pellet matrices requires

evaluation of the trade-off between the increase in calorific value, mechanical stability, and the emissions profile associated with their combustion.

Table 10. Properties of manufactured pellets.

Properties \ Samples	W00	W05	W10	W15	W20	W25
Origin *	Mix (5.1): 10% Pow, 10% Piw and 80% Rw	Mix (5.1): 9.5% Pow, 9.5% Piw, 76% Rw and 5% SCGs	Mix (5.1): 9% Pow, 9% Piw, 72% Rw and 10% SCGs	Mix (5.1): 8.5% Pow, 8.5% Piw, 68% Rw and 15% SCGs	Mix (5.1): 8% Pow, 8% Piw, 64% Rw and 20% SCGs	Mix (5.1): 7.5% Pow, 7.5% Piw, 60% Rw and 25% SCGs
Dimensions D [mm] L [mm]	D06, 6.0 mm $\pm$ 1.0 mm 3.15 mm $\leq$ L $\leq$ 40 mm					
Moisture, M [% of mass as received]	M08					
Ash, A [% of mass on dry basis]	A3.0			A2.0		
Mechanical durability, DU [% of mass of pellets after testing]	DU96.5	DU96.5	DU96.0	DU95.0	DU95.0- (94.6)	DU95.0- (93.2)
Amount of fines, F [% of mass, <3.15 mm]	F1.0					
Additives [% of mass of pressing mass]	5% cornstarch					
Bulk density, BD [kg/m ³ as received]	BD550	BD600	BD580	BD550	BD500	BD550
Net calorific value, Q [MJ/kg]	18.16 $\pm$ 0.28 ^a	18.17 $\pm$ 0.05 ^a	18.14 $\pm$ 0.13 ^a	18.13 $\pm$ 0.17 ^a	18.19 $\pm$ 0.03 ^a	18.26 $\pm$ 0.18 ^a
Nitrogen, N [% of mass on dry basis]	N2.0 N $\leq$ 2.0%					
Sulfur, S [% of mass on dry basis]	S0.30 S $\leq$ 0.30%					
Chlorine, Cl [% of mass on dry basis]	Cl0.40 $\leq$ 0.40					
Fixed Carbon, C [% of mass on dry basis]	44.35	42.15	39.96	37.77	35.58	33.38
Volatile matter, VM [% of mass on dry basis]	92.30 $\pm$ 1.93 ^a	92.34 $\pm$ 1.67 ^a	92.36 $\pm$ 1.91 ^a	92.39 $\pm$ 1.88 ^a	91.37 $\pm$ 1.81 ^a	90.87 $\pm$ 1.21 ^a

* Pow: poplar woody biomass (1.1.3.3); Piw: pine woody biomass (1.1.3.4); Rw: mixture of used wood with and without chemical treatment (1.3.3); SCGs: spent coffee grounds (3.2.2.1). ^a Values are expressed as mean $\pm$ standard deviation ($n = 2$). Means within the same row sharing a common superscript letter (a) are not significantly different according to Tukey's HSD post-hoc test ($p > 0.05$).

It is important to note that, in terms of dimensions and moisture content, all samples fall within the specified ranges and are classified as D06 pellets (diameter of 6.0 mm $\pm$ 1.0 mm and a length between 3.15 mm and 40.0 mm) and M08 (moisture content below 8.0% by mass, as received). These results are consistent with those reported by the scientific community: (D06, M08) [21,22], (D06, M10) [26,27], (D06, M12) [30] and (D06, M15 for concentrations of up to 40% SCGs) [27]. From a physical and energetic perspective, a trade-off relationship was observed between the net calorific value (Q) and

mechanical durability (*DU*) as the proportion of coffee waste increases (see Figure 3). The *Q* value exhibited non-linear behavior, described by a third-order polynomial model ($y = 0.0037x^3 - 0.0271x^2 + 0.0506x + 18.137$; $R^2 = 0.9494$). Following a slight fluctuation among the intermediate formulations (W05–W15), the calorific value increased markedly, reaching a maximum of 18.26 MJ/kg in formulation W25, compared with 18.16 MJ/kg in the control sample (W00). Conversely, *DU* exhibited a statistically significant linear decrease as the proportion of SCGs increased ($y = -0.7577x + 98.255$; $R^2 = 0.9342$), decreasing progressively from 97.4% in W00 to 94.6% in W20 and 93.2% in W25. This behavior suggests that, although the incorporation of SCGs can enhance the energy density of the pellet, it negatively affects the mechanical interlocking of the lignocellulosic fibers during densification.

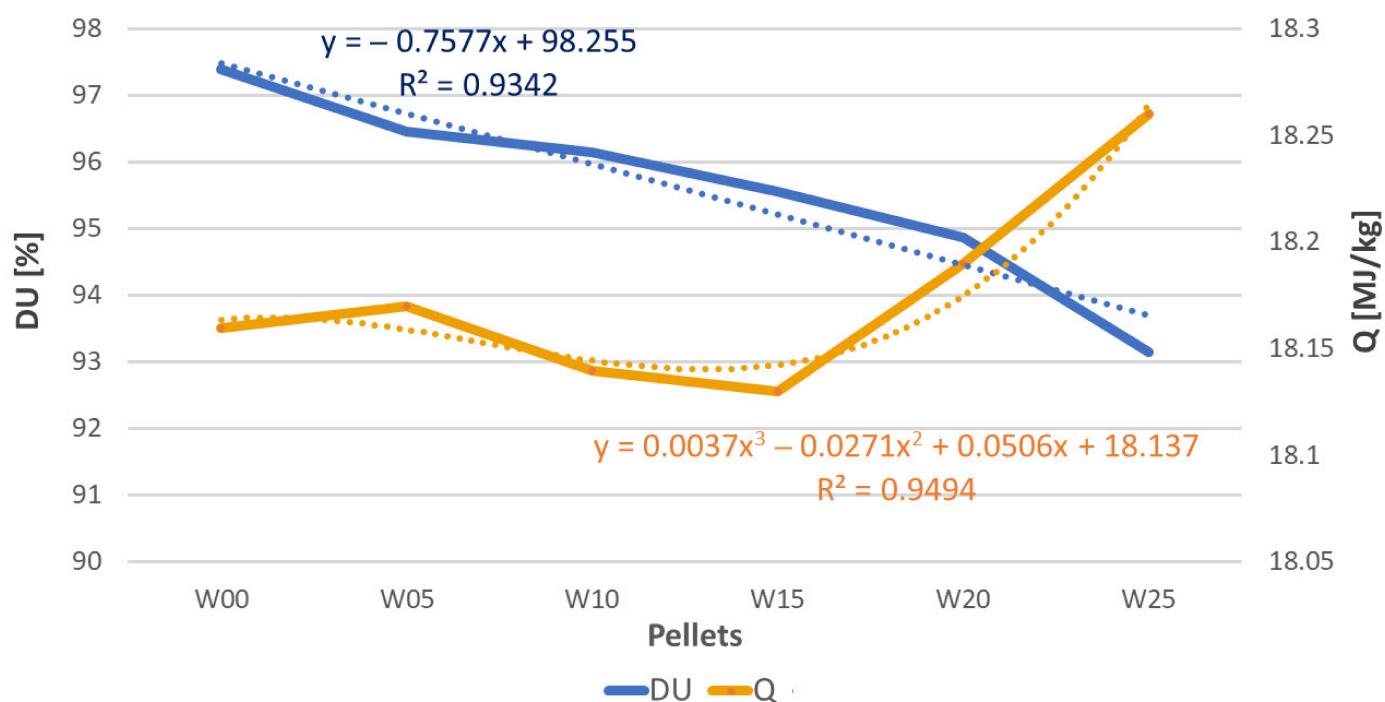


Figure 3. Mechanical durability (*DU*) and net calorific value (*Q*) as a function of spent coffee grounds (SCGs) incorporation ratio (W00–W25). Dotted lines represent the linear regression model for *DU* ($R^2 = 0.9342$) and the polynomial regression model for *Q* ($R^2 = 0.9494$).

This opposing trend is consistent with previous findings reported in the scientific literature. Iryani et al. [19] produced wood sawdust pellets in which increasing the SCGs proportion from 25.0% to 100.0% increased the *Q* value from 21.37 MJ/kg to 22.94 MJ/kg, but reduced mechanical durability (from 97.02% to 95.23%), reaching levels that prevented commercial classification at SCGs concentrations exceeding 50.0%. Similarly, Lachman et al. [26], reported that mixtures of spruce sawdust with SCGs substitution rates of 50–75% did not meet the required quality parameters (*DU*: 86–75%), despite exhibiting high calorific values (18.27–19.46 MJ/kg). Woo et al. [23] likewise reported that pine sawdust blends met Class A or B requirements only at SCGs additions below 30.0%, whereas higher proportions resulted in a substantial deterioration in durability, reaching values as low as 67.9%. This loss of cohesion is commonly associated with the lipids and free oils content in SCGs, which can act as lubricants and inhibit the natural hydrogen bonds in lignin, unless binding additives are introduced. This was validated by Kristanto and Wijaya [18], who produced stable pellets (*DU*: 99.0%, *Q*: 19.33 MJ/kg) by combining coffee by-products: 20% silverskin, 75% SCGs and 5% starch. Park et al. [29,32] have described similar behavior when combining SCGs with agricultural residues from pepper stems (PP) and perilla (PR),

where high doses of coffee residue shifted the formulations into lower commercial quality categories: 90% PP–10% SCGs (*DU*: 99.4%, *Q*: 19.21 MJ/kg), 80% PP–20% SCGs (*DU*: 98.4%, *Q*: 19.43 MJ/kg) y 70% PP–30% SCGs (*DU*: 98.2%, *Q*: 20.35 MJ/kg) [27]; 50% PP–50% SCGs (*DU*: 98.6%, *Q*: 20.35 MJ/kg) y 50% PR–50% SCGs (*DU*: 98.1%, *Q*: 20.72 MJ/kg) [30].

According to ISO 17225-2 [80], a Type B wood pellet must have a mechanical durability of a minimum of 96.5%, while according to ISO 17225-6 [58], a Class B non-wood pellet must have a durability of 96.0% or greater. Based on this regulatory framework, the W05 and W10 formulations are established as viable alternatives, as they maintain mechanical stability compatible with commercial requirements for non-wood biofuels.

Meanwhile, the bulk density (*BD*) remained within a technically acceptable range (500–600 kg/m³). The slight fluctuations observed suggest that the extrusion process becomes less consistent at higher SCGs substitution rates. In contrast, the fine content (*F*) of less than 1.0% is an optimal value in all samples and comparable to the standard for high-quality wood pellets (Class A).

These physical properties are directly influenced by the structural matrix of the biomass with which SCGs are combined. For example, while Wu [20] reported proportional increases in *BD* (710–760 kg/m³) when mixing spent tea grounds and SCGs (20–100%), Kougioumtzis et al. [29] and Iryani et al. [19] (Table 11) show that co-pelletization with different types of biomasses significantly increases bulk density (630–1143.5 kg/m³), mainly due to the greater compactability of woody lignocellulosic fibers. Furthermore, although the regulations for Class B non-woody pellets establish a maximum fines content of 3.0%, a comparative analysis of the literature highlights the difficulty of pelletizing high proportions or pure SCGs. Formulations containing 100% SCGs increase the *F* to levels ranging from 2.4% to 9.1% [27,30], a problem that is drastically exacerbated by severe structural incompatibilities, such as the cases reported by Alves Pinto et al. [28] and Kasantiuk [81] using orange juice waste (21.3–93.7%) or tapioca starch (4.0%). These findings confirm the crucial importance of co-pelletizing SCGs with a structurally supportive biomass capable of agglomerating the fine particulate material and mitigating the physical degradation of the biofuel.

One of the most notable competitive advantages of introducing SCGs was the reduction in ash content (*A*) as its proportion increased. This provides a direct operational and maintenance benefit for thermal combustion systems (boilers and stoves) by mitigating fouling and slagging phenomena. Samples W00 and W05 (*A* ≤ 3.0%), along with the W10 through W25 series (*A* ≤ 2.0%), comfortably met the maximum limit of 6.0% established by ISO 17225-6 [58], allowing them to be classified as Class A pellets within the non-wood material category.

The experimental results are consistent with trends reported in the scientific literature, which the relatively low ash content, *A*, of SCGs acts effectively as a diluent. However, the final viability of the pellet is strictly influenced by the chemical and structural nature of the complementary biomass. As reported by Kougioumtzis et al. [29], when co-pelletizing SCGs with maize residues—which are characterized by a high mineral content—*A* was reduced to levels compatible with the standard only at SCGs inclusion rates exceeding 70% (*A*: 5.8%). In contrast, in mixtures of SCGs with *Miscanthus* (MI), none of the evaluated formulations met regulatory requirements, with an *A* level of 9.2% for the 70% MI–30% SCGs mixture and 6.8% for the 50% MI–50% SCGs formulations. These results demonstrate that, although the addition of SCGs optimizes the inorganic profile of the biofuel, the selection of the base biomass feedstock remains the limiting factor for commercial standardization.

Table 11. Benchmark data of bulk density (BD) and fine content (F) for alternative biomass pellets co-pelletized with SCGs as reported in the literature.

Biomass	Mixture	BD [kg/m ³]	Ref.	Biomass	Mixture	F [%]	Ref.
Forest residues (FR)	90% FR–10% SCGs	687.0	[29]	Red peppers stems (PP)	90% PP–10% SCGs	0.2	[27]
	70% FR–30% SCGs	701.0			80% PP–20% SCGs	0.2	
	50% FR–50% SCGs	695.0			70% PP–30% SCGs	0.2	
	30% FR–70% SCGs	666.0			60% PP–40% SCGs	0.1	
	10% FR–90% SCGs	725.0			100% SCGs	2.4	
Sawmill residues (SR)	90% SR–10% SCGs	712.0		Pepper stem (PP)/Rice chaff (CR)/Perilla stem (PR)	50% PP–50% SCGs	0.2	[30]
	70% SR–30% SCGs	715.0			50% CR–50% SCGs	0.3	
	50% SR–50% SCGs	720.0			50% PR–50% SCGs	0.2	
	30% SR–70% SCGs	742.0			100% SCGs	9.1	
Urban prunings (U)	90% U–10% SCGs	648.0		Orange juice waste (OJW)	90% OJW–10% SCGs	21.3	[28]
	70% U–30% SCGs	671.0			50% OJW–50% SCGs	93.7	
	50% U–50% SCGs	664.0		Tapioca starch (Ts)	10% Ts–90% SCGs	4.0	[81]
Maize residues (Ma)	90% Ma–10% SCGs	662.0					
	70% Ma–30% SCGs	716.0					
	50% Ma–50% SCGs	708.0					
	30% Ma–70% SCGs	715.0					
	10% Ma–90% SCGs	682.0					
Peach prunings (RP)	90% RP–10% SCGs	630.0	[19]				
	70% RP–30% SCGs	652.0					
	50% RP–50% SCGs	706.0					
	30% RP–70% SCGs	668.0					
	10% RP–90% SCGs	714.0					
Wood sawdust (WS)	75% WS–25% SCGs	905.3	[19]				
	50% WS–50% SCGs	986.2					
	100% SCGs	1143.5					

3.2. Elemental Chemical Analysis and Operational Implications

Regarding the chemical analysis, fixed carbon (C) decreases significantly from 44.35% to 33.38%. At the same time, the volatile matter (VM) showed a slight decrease with the increase in SCGs, decreasing from 92.30% to 90.87%. These values confirm that, despite structural variations, the formulations maintain high thermal reactivity during the devolatilization phase—a characteristic behavior of waste biomass that promotes rapid fuel ignition.

From an environmental impact and gaseous emissions point of view, sulfur (S), nitrogen (N), and chlorine (Cl) contents are critical factors. Table 12 summarizes the reports by many authors regarding the N, S, and Cl content of alternative biomass pellets co-pelletized with SCGs.

Table 12. Benchmark data of nitrogen (N), sulfur (S) and chlorine (Cl) content for alternative biomass pellets co-pelletized with SCGs as reported in the literature.

Biomass	Mixture	N [%]	S [%]	Cl [%]	Ref.
Pine sawdust (PS)	90% PS–10% SCGs		0.02	0.01	[23]
	70% PS–30% SCGs		0.04	0.01	
	50% PS–50% SCGs		0.08	<0.01	
	30% PS–70% SCGs		0.11	<0.01	
	10% PS–90% SCGs		0.11	<0.01	
	100% SCGs		0.12	<0.01	
Forest residues (FR)	90% FR–10% SCGs	0.78	0.06	0.02	
	70% FR–30% SCGs	1.43	0.11	0.02	
	50% FR–50% SCGs	2.26	0.16	0.02	
	30% FR–70% SCGs	2.53	0.18	0.02	
	10% FR–90% SCGs	2.96	0.20	0.02	
Sawmill residues (SR)	90% SR–10% SCGs	0.43	0.03	0.02	
	70% SR–30% SCGs	1.14	0.07	0.02	
	50% SR–50% SCGs	1.88	0.10	0.02	
	30% SR–70% SCGs	2.51	0.14	0.01	
Urban prunings (U)	90% U–10% SCGs	0.80	0.05	0.02	[29]
	70% U–30% SCGs	1.60	0.11	0.02	
	50% U–50% SCGs	2.11	0.13	0.02	
Maize residues (Ma)	90% Ma–10% SCGs	1.16	0.10	0.25	
	70% Ma–30% SCGs	1.99	0.14	0.18	
	50% Ma–50% SCGs	2.15	0.14	0.12	
	30% Ma–70% SCGs	2.76	0.16	0.07	
	10% Ma–90% SCGs	3.14	0.17	0.04	
Peach prunings (RP)	90% RP–10% SCGs	1.22	0.07	0.01	
	70% RP–30% SCGs	1.84	0.11	0.01	
	50% RP–50% SCGs	2.30	0.14	0.01	
	30% RP–70% SCGs	2.71	0.17	0.02	
	10% RP–90% SCGs	3.02	0.19	0.01	
Miscanthus (MI)	70% MI–30% SCGs	1.32	0.10	0.13	
	50% MI–50% SCGs	1.94	0.11	0.08	
Spruce sawdust (SS)/FFP2 masks (FM)/Single-use masks (SM)	90% SS–2.5% FM–2.5% SM–5% SCGs	0.04	0.012	0.01	[21]
	80% SS–5% FM–5% SM–10% SCGs	0.14	0.022	0.071	
Garden chaff (G)/Rapeseed straw of the Sherpa variety (R)	75% R + 25% SCGs	1.14	0.40		[31]
	50% R + 50% SCGs	1.37	0.29		
	50% G + 50% SCGs	1.80	0.27		
	100% SCGs	2.19	0.21		

Table 12. Cont.

Biomass	Mixture	N [%]	S [%]	Cl [%]	Ref.
Pepper stem (PP)/Rice chaff (CR)/Perilla stem (PR)	50% PP–50% SCGs	1.40	0.14	0.22	[30]
	50% CR–50% SCGs	1.10	0.11	0.08	
	50% PR–50% SCGs	1.10	0.10	0.08	
	100% SCGs	2.00	0.05	<0.01	
Red pepper stems (PP)	90% PP–10% SCGs	1.70	0.09	0.29	[27]
	80% PP–20% SCGs	1.80	0.09	0.27	
	70% PP–30% SCGs	1.70	0.07	0.24	
	60% PP–40% SCGs	2.80	0.06	0.17	
	100% SCGs	3.00	0.08	0.02	
<i>Solidago canadensis</i> L. (Sc)/ <i>Heracleum sosnowskyi</i> Manden (Hs)	94% Sc + 6% SCGs	0.47	0.19		[32]
	94% Hs + 6% SCGs	0.68	0.01		
	90% Hs + 10% SCGs	0.74	0.01		
	70% Hs + 30% SCGs	1.04	0.04		
	50% Hs + 50% SCGs	1.35	0.06		

An increase in SCGs slightly raises the S content (0.034–0.039%), remaining within ranges that are insignificant for SO_x formation, consistent with the results obtained for pine sawdust-based pellets by Woo et al. [23] or from pellets made from various biomass sources produced by Kougioumtzis et al. (forest, sawmill, and maize residues; urban and peach prunings; or *Miscanthus*) [29]. However, the N content consistently remained around the 2.0% threshold, significantly higher than in virgin wood pellets, where it is typically $\leq 0.3\%$ for A1-type pellets and $\leq 1.0\%$ for B-type pellets [80]. This compositional characteristic represents one of the main limitations of the developed blends, as the presence of nitrogen bound to the fuel could lead to increased nitrogen oxide (NO_x) emissions during thermal utilization—an aspect that must be controlled through combustion air optimization systems or flue gas aftertreatment. An increase in nitrogen as the percentage concentration of SCGs rises is a common trend, as reported in the results of other studies [21,27,29–32].

As for Cl, it ranges from 0.051 (W00) to 0.040 (W25), showing a slight decrease as the SCGs content increases and comfortably meeting the regulatory limits for non-woody pellets [58]. This downward trend in chlorine content depends largely on the type of woody biomass used in the formulations, as there are cases where the amount of chlorine—0.02%—remains constant regardless of the SCGs content, such as when forest residues or urban prunings have been used [29].

The obtained results for the different pelletized mixtures can be categorized under ISO 17225-6 [58] (specific to non-wood pellets) because it is the only ISO standard for pellets that includes mixtures of woody and non-woody biomass; therefore, the classification of the pellets' origin includes the digit 5, corresponding to “combinations and mixtures”. Additionally, this standard permits solid biofuel to contain chemically treated material, provided that it is declared.

Under this regulatory framework, the formulations ranging from the control sample to the variant containing 10% SCGs (W00–W10) strictly comply with the limits established for each Class B property. Specifically, these samples meet the thresholds specified for diameter (D06–D25, $D \pm 1$ mm), length (3.15–40 mm), moisture content ($M15 \leq 15\%$), ash content ($A10 \leq 10\%$), mechanical durability ($DU96.0 \geq 96.0\%$), fines content ($F3.0 \leq 3.0\%$), additive concentration ($\leq 5\%$; type and quantity to be declared), bulk density ($BD550 \geq 550$ kg/m³),

net calorific value ($Q_{14.5} \geq 14.5$ MJ/kg), nitrogen ($N_{2.0} \leq 2.0\%$), sulfur ($S_{0.30} \leq 0.30\%$), and chlorine ($Cl_{0.40} \leq 0.40\%$).

Based on these criteria, the W10 formulation emerges as the optimal formulation in this study. This formulation maximizes the SCGs incorporation rate while maintaining a favorable technical balance: it preserves mechanical durability within the applicable regulatory limit (96.0%), an adequate bulk density (580 kg/m^3), and a competitive net calorific value, without causing significant increases in sulfur or nitrogen contents or compromising the physical stability of the biofuel.

Conversely, although the formulations with higher SCGs substitution rates (W20 and W25) provide a higher overall energy potential, they substantially compromise the mechanical integrity of the pellets. This structural limitation could result in increased generation of fines and dust during storage, handling, and transport through feed silos, potentially increasing the risk of mechanical blockages and/or inefficient combustion in thermal systems.

3.3. Life-Cycle Impact Indicators and Critical Points in Pellet Manufacturing

The initial stages of biomass procurement, transportation, and mechanical processing account for the highest energy demand and, consequently, represent the main contributors to overall environmental impact. When the components of the wood matrix are evaluated individually, using 1 kg as the reference unit, the preparation of virgin wood results in a total impact of 70.48 mPt, whereas the processing of recycled wood results in an impact of only 1.98 mPt. These results clearly demonstrate that incorporating 80% recycled wood into the base formulation fulfills a fundamental eco-design criterion by reducing pressure on primary forest resources and reintegrating an industrial byproduct into the production cycle. Figure 4 shows the damage assessment in terms of endpoints for the woods used, demonstrating that recycled wood has 97.18% less impact than virgin wood.

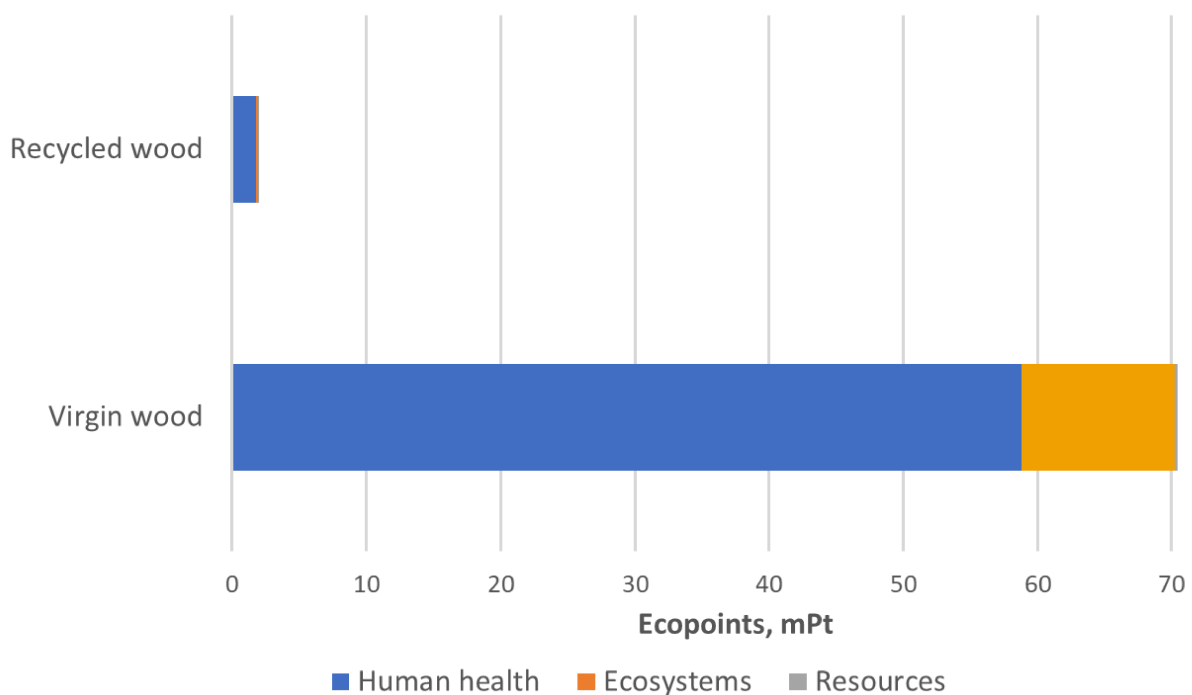


Figure 4. Single-score assessment of environmental impact from processing 1 kg of virgin wood and 1 kg of recycled wood.

In terms of carbon footprint, the quantification of greenhouse gas emissions using the IPCC 2013 GWP 100a (v.1.03) method showed that the individual raw materials ex-

hibit different environmental profiles prior to blending. The wood matrix (20% virgin wood and 80% recycled wood) has a carbon footprint of 0.39 kg CO₂ eq per kg of wood, while SCGs and cornstarch have significantly lower contributions, at 0.27 kg CO₂ eq and 1.11 kg CO₂ eq, respectively.

When analyzing the environmental impact profile of the pellets produced, the main contributors are electricity consumption throughout the production process and the use of virgin wood, despite the relatively small proportion of the latter in the formulations. Both factors substantially outweigh the impact associated with the road transportation of the wood raw materials, even under a demanding logistics scenario involving transportation distances exceeding 200 km. In particular, electricity consumption at the pilot plant accounts for between 46.93% (W00) and 51.30% (W25) of the total impact, depending on the SCGs substitution rate, with the optimal formulation reaching 48.58% (W10). Meanwhile, the environmental impact attributable to the use of virgin wood ranges from 40.53% (W00) to 34.58% (W25). In contrast, the impact arising from transportation requirements accounts for only a minor fraction, ranging from 4.79% (W00) to 4.38% (W25).

As illustrated in the radar charts in Figure 5, the progressive incorporation of SCGs significantly alters the relative weight of these environmental stress factors: as the SCGs concentration increases, the overall environmental impact associated with the use of virgin wood is mitigated. Consequently, due to the substitution of raw material, the relative contribution of electricity consumption increases proportionally (Figure 5a), while the percentage weight of wood transportation decreases systematically as SCGs increase (Figure 5b).

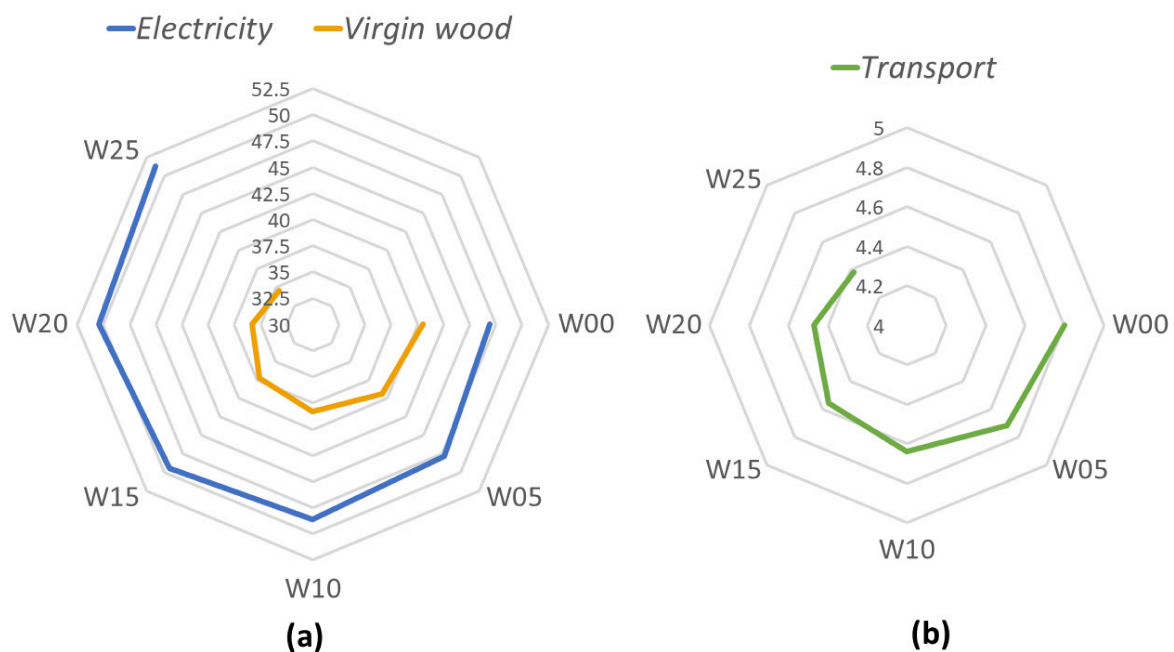


Figure 5. Total associated impact as a percentage: (a) electricity and virgin wood; (b) transport. (Note that for readability, different scale ranges are used in subfigures (a,b)).

The consolidated absolute environmental impacts for 1 t of pellets and the performance of the different categories across the five formulations are summarized in Table 13. The most critical finding of the LCA is the consistent negative correlation between the increase in SCGs content (from W00 to W25) and the cumulative environmental burden, as shown in Figure 6). Across the three major Endpoint damage categories (Human health, Ecosystems and Resources), the environmental impact decreases linearly as the proportion of agro-industrial waste increases, fitting linear regression models with absolute goodness-of-fit ($R^2 = 1.00$). Specifically, at the maximum substitution of 25% SCGs (W25) the damage

to Human Health decreases by 11.60% compared with the control formulation (W00), while the impact on *Ecosystems* decreases by 15.84% and, the impact on resource scarcity (Resources) decreases by 10.21%.

Table 13. Characterization and damage assessment in 1 t of pellet manufacturing/ReCiPe 2016 Endpoint (H) V1.03/World (2010) H/A.

Damage Category	Impact Category	Unit	W00	W05	W10	W15	W20	W25
Human Health	Global warming, Human health	DALY	0.00045405	0.000448447	0.000442867	0.000437277	0.000431685	0.000426094
	Stratospheric ozone depletion	DALY	4.22326×10^{-7}	4.19915×10^{-7}	4.1751×10^{-7}	4.15102×10^{-7}	4.12693×10^{-7}	4.10285×10^{-7}
	Ionizing radiation	DALY	1.60878×10^{-6}	1.59318×10^{-6}	1.5777×10^{-6}	1.56216×10^{-6}	1.54663×10^{-6}	1.53109×10^{-6}
	Ozone formation, Human health	DALY	1.67244×10^{-6}	1.64048×10^{-6}	1.60859×10^{-6}	1.57667×10^{-6}	1.54475×10^{-6}	1.51282×10^{-6}
	Fine particulate matter formation	DALY	0.001282377	0.001244109	0.001205882	0.001167635	0.001129387	0.00109114
	Human carcinogenic toxicity	DALY	5.80953×10^{-5}	5.78473×10^{-5}	5.76033×10^{-5}	5.73574×10^{-5}	5.71114×10^{-5}	5.68655×10^{-5}
	Human non-carcinogenic toxicity	DALY	7.20806×10^{-5}	7.27074×10^{-5}	7.33386×10^{-5}	7.39676×10^{-5}	7.45966×10^{-5}	7.52256×10^{-5}
	Water consumption, Human health	DALY	8.14666×10^{-6}	8.06953×10^{-6}	7.99499×10^{-6}	7.91918×10^{-6}	7.84334×10^{-6}	7.76752×10^{-6}
	Total	DALY	0.001878452	0.001834834	0.00179129	0.001747709	0.001704128	0.001660547
Ecosystems	Global warming, Terrestrial ecosystems	species.yr	1.36997×10^{-6}	1.35306×10^{-6}	1.33622×10^{-6}	1.31935×10^{-6}	1.30247×10^{-6}	1.2856×10^{-6}
	Global warming, Freshwater ecosystems	species.yr	3.74239×10^{-11}	3.69619×10^{-11}	3.65019×10^{-11}	3.60409×10^{-11}	3.55799×10^{-11}	3.51189×10^{-11}
	Ozone formation, Terrestrial ecosystems	species.yr	2.40646×10^{-7}	2.36004×10^{-7}	2.31372×10^{-7}	2.26735×10^{-7}	2.22098×10^{-7}	2.17461×10^{-7}
	Terrestrial acidification	species.yr	6.11771×10^{-7}	6.04786×10^{-7}	5.97836×10^{-7}	5.90869×10^{-7}	5.83902×10^{-7}	5.76934×10^{-7}
	Freshwater eutrophication	species.yr	1.14303×10^{-7}	1.13645×10^{-7}	1.12994×10^{-7}	1.12339×10^{-7}	1.11684×10^{-7}	1.11029×10^{-7}
	Marine eutrophication	species.yr	3.15384×10^{-10}	3.17426×10^{-10}	3.19469×10^{-10}	3.21511×10^{-10}	3.23554×10^{-10}	3.25596×10^{-10}
	Terrestrial ecotoxicity	species.yr	1.4791×10^{-8}	1.4606×10^{-8}	1.4421×10^{-8}	1.4236×10^{-8}	1.4052×10^{-8}	1.3867×10^{-8}
	Freshwater ecotoxicity	species.yr	1.0306×10^{-8}	1.0771×10^{-8}	1.1238×10^{-8}	1.1704×10^{-8}	1.2169×10^{-8}	1.2635×10^{-8}
	Marine ecotoxicity	species.yr	2.09296×10^{-9}	2.1776×10^{-9}	2.26252×10^{-9}	2.34731×10^{-9}	2.43209×10^{-9}	2.51687×10^{-9}
	Land use	species.yr	4.84237×10^{-6}	4.64209×10^{-6}	4.44182×10^{-6}	4.24154×10^{-6}	4.04127×10^{-6}	3.84099×10^{-6}
	Water consumption, Terrestrial ecosystem	species.yr	3.3911×10^{-8}	3.3602×10^{-8}	3.3307×10^{-8}	3.3005×10^{-8}	3.2702×10^{-8}	3.24×10^{-8}
	Water consumption, Aquatic ecosystems	species.yr	2.55698×10^{-12}	2.53291×10^{-12}	2.50956×10^{-12}	2.48586×10^{-12}	2.46216×10^{-12}	2.43845×10^{-12}
	Total	species.yr	7.24052×10^{-6}	7.0111×10^{-6}	6.78183×10^{-6}	6.55249×10^{-6}	6.32314×10^{-6}	6.0938×10^{-6}
Resources	Mineral resource scarcity	USD2013	0.21569077	0.21512336	0.21456831	0.21400723	0.213446	0.21288484
	Fossil resource scarcity	USD2013	36.174534	35.431626	34.690115	33.947922	33.205713	32.463512
	Total	USD2013	36.39022477	35.64674936	34.90468331	34.16192923	33.419159	32.67639684

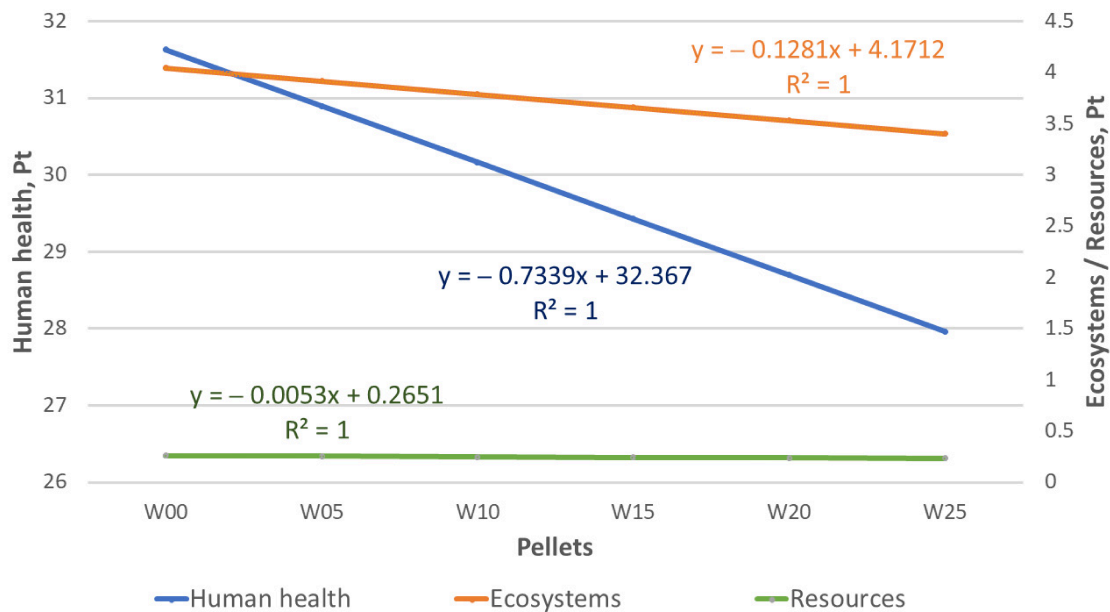


Figure 6. Endpoint environmental damage scores (Human health, Ecosystems, and Resources) in ecopoints (Pt) as a function of SCGs incorporation ratio in pellet formulations (W00–W25). Dotted lines represent linear regression models ($R^2 = 1.00$). Note: Human health is plotted on the primary y-axis (left); Ecosystems and Resources are plotted on the secondary y-axis (right).

At the level of midpoint indicators, the environmental impact profile is strongly influenced by the categories of Global Warming, Human Health, and Fine Particulate Matter Formation. The marked reduction in the Global Warming score confirms that SCGs have a significantly lower carbon footprint during the procurement stage, which can be attributed to their methodological classification as “burden-free” waste, in contrast to the environmental burden associated with virgin wood.

Meanwhile, the Fine Particulate Matter Formation category, although showing a decreasing trend with increasing SCGs content, maintains relatively high absolute values throughout the production process. However, this emission profile does not compromise the viability of the biofuel, as supported by the elemental chemical analysis, which showed that the total nitrogen content of all samples remained below the critical limit of 2.0%.

Environmental impacts within the Ecosystems damage category are dominated almost exclusively by the Land use indicator, mainly due to the change in soil quality and biological properties associated with forest conversion for agricultural purposes. However, it is interesting to note that minority subcategories such as Freshwater ecotoxicity show a slight increase, rising from 0.0057 to 0.0070. Although this order of magnitude is marginal in the global life cycle assessment, it reveals that the collection logistics or the wet pretreatment of SCGs introduce a small nutrient load into the aquatic environment that the dry recycled wood matrix does not generate.

Finally, the Resources category—which records the highest absolute values in the study—is driven 99.9% by the Fossil resource scarcity indicator. The drastic reduction achieved through the eco-design of the pellet—which represents a net savings of approximately 38 USD₂₀₁₃ per reference unit—empirically demonstrates that the integration of local waste streams such as SCGs effectively decouples the biofuel supply chain from dependence on secondary fossil energy carriers, thereby optimizing the product’s overall sustainability.

The emission kinetics of fine particulate matter and CO₂ are intrinsically linked to the physicochemical properties of the solid biofuel and to the hydrodynamic conditions of the combustion process. In this regard, ensuring that the pellets developed comply

with the stringent limits set for Class B under the ISO 17225-6 standard is a critical factor in promoting complete combustion, thereby mitigating the formation of unburned gases, soot and fugitive emissions associated with incomplete pyrolysis. With regard to the standard's critical parameters, a moisture content exceeding 15.0% results in a direct reduction in the net calorific value, as a significant proportion of the thermal energy released must be used to provide the latent heat of vaporization of the endogenous water. Furthermore, the ash content represents the non-combustible mineral fraction; values above 10.0% usually indicate a high proportion of bark, soil or exogenous impurities in the raw materials. From an operational perspective, this excess of inorganic matter promotes slag build-up, increases the risk of sintering and reduces heat transfer efficiency in the boiler heat exchanger. Finally, mechanical durability is an indirect indicator of the pellet's structural stability during storage and transport; a value below 96.0% accelerates the processes of mechanical degradation and the generation of fines. The presence of these sub-millimeter-sized particles can alter the permeability of the combustion bed, causing an irregular feed rate and localized pressure drops in the boiler furnace. This phenomenon not only destabilizes the stoichiometry of the reaction, increasing emission rates, but also substantially increases operating costs for the end user due to the increased frequency of corrective maintenance and losses of usable fuel mass.

Figure 7 shows that increasing the SCGs content positively influences the reduction in the overall environmental impact, following a linear trend from 35.94 Pt for sample W00, containing 0% SCGs, to 31.60 Pt for sample W25, containing 25% SCGs. This reduction corresponds to a net decrease of 12.07% in ecopoints, while the optimal formulation (W10) results in a 4.83% reduction, with an overall impact of 34.20 Pt. Therefore, the incorporation of SCGs as an additive or substitute for wood in pellet production provides an environmental benefit. The results obtained using the ReCiPe 2016 assessment method support the hypothesis that the valorization of coffee industry waste can improve the circularity and overall environmental performance of the biofuel.

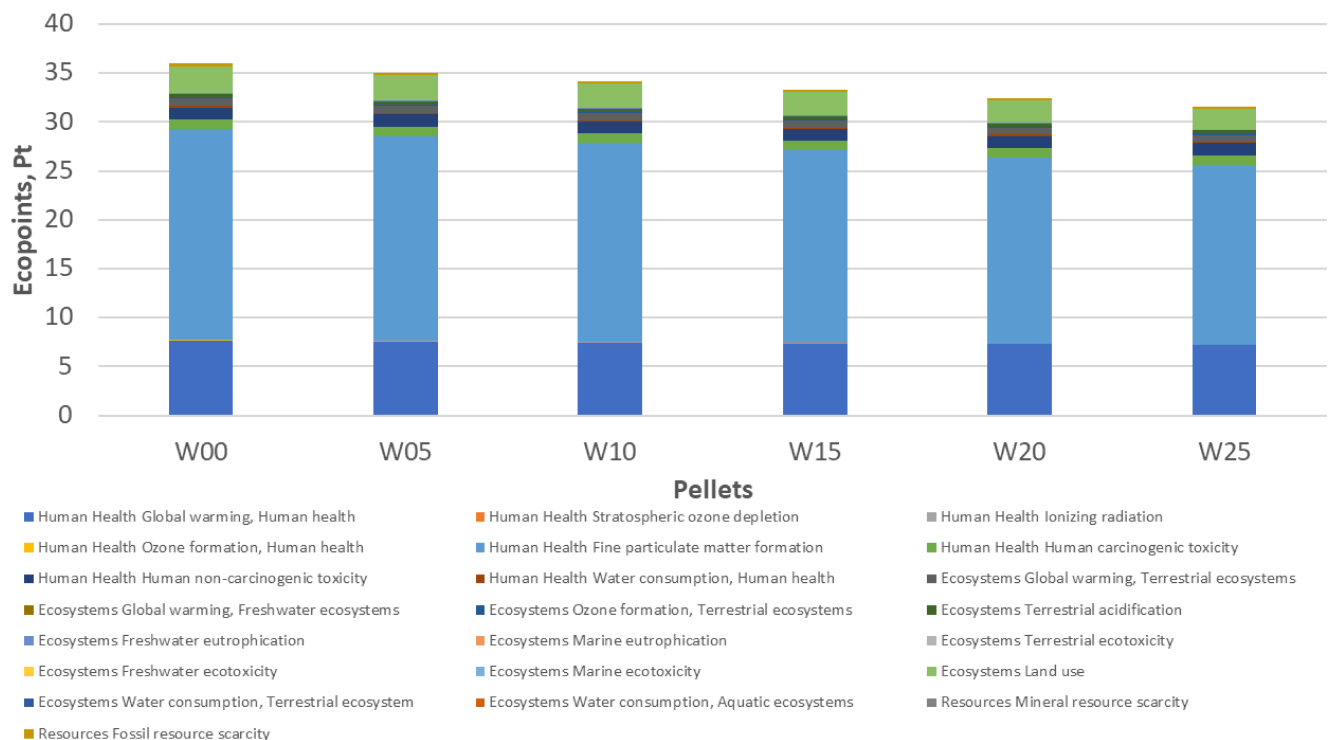


Figure 7. Single-score impact analysis based on the studied pellet blends.

Likewise, the detailed analysis identified the five specific impact categories contributing most significantly to the overall environmental damage: Fine Particulate Matter Formation, Global Warming—Human Health, Land Use, Human Non-Carcinogenic Toxicity, and Human Carcinogenic Toxicity. The prevalence of these indicators highlights that the primary damage vector in the pellet's life cycle affects human health. This trend is closely linked to emissions from long-distance logistics transport of wood, as well as emissions particular to the electricity mix in the inventory and the logged forest; the trend is significantly mitigated as SCGs (a locally sourced, low-emission material) gain prominence in the mix.

The electricity consumption calculated for the production of 1 kg of the pellets developed in this study stood at approximately 0.934 kWh. This energy demand is mainly associated with the unit operations involved in processing the woody raw materials and waste, specifically in the crushing and grinding stages of virgin wood logs and recycled material, which are necessary to achieve an optimal particle size distribution for pelletization. When comparing this figure with the recent scientific literature, significant variability is observed depending on the type of biomass and the system boundaries considered. On the one hand, the consumption of 0.934 kWh/kg is higher than that reported by Klitou et al. [38] and Rajabi et al. [69] for pellets composed exclusively of SCGs, who quantified electricity demands of 0.200 kWh/kg and 0.622 kWh/kg, respectively. This discrepancy is attributable to the higher specific resistance to comminution exhibited by the virgin wood fraction incorporated into our matrix, compared with the pre-processed, granular structure of the coffee waste.

Furthermore, compared with the results reported by Svedovs et al. [39] in Latvia for various alternative regional biomass sources, the value obtained emerges as an intermediate and highly competitive indicator. The authors reported specific energy consumption values that vary substantially depending on the nature of the resource, ranging from lower values such as sunflower husks (0.30 kWh/kg), to markedly higher requirements for fibrous materials or those with low bulk density, such as wood shavings (1.18 kWh/kg), brewer's spent grain (1.63 kWh/kg), reeds (1.67 kWh/kg), straw (1.71 kWh/kg), hemp (1.85 kWh/kg), Canadian goldenrod (2.46 kWh/kg), dry leaves (3.45 kWh/kg) and grass (5.05 kWh/kg). This intermediate position validates the technical and energy viability of the proposed co-pelletization process, underpinning the need to conduct a more in-depth LCA to elucidate the environmental impact profiles and the competitive advantages associated with the incorporation of SCGs.

According to the environmental impact assessment using the ReCiPe 2016 Endpoint (H/A) method, a positive and progressive effect resulting from the addition of SCGs was observed: as the percentage of coffee waste substitution increased, the overall impact decreased systematically (from 35.9 Pt in W00 to 31.6 Pt in W25). However, the absolute impact values observed (34.20 Pt for W10 or its equivalent of 468.20 kg CO₂ eq/t under the IPCC methodology) are higher than the unit profiles reported by Svedovs et al. [39], whose impacts for Latvian biomass ranged from 4.58 Pt (sunflower husks) to 30.74 Pt (reeds), with a value of 22.86 Pt for wood shavings.

An analysis of the distribution of impacts by damage category in our study is entirely consistent with the findings of Svedovs et al.: impacts associated with Human Health exert an overwhelming influence on the overall environmental profile, driven critically by the subcategory Fine particulate matter formation, followed in magnitude by Global warming, Human Health. This high footprint is a direct result of the upstream processes involved in virgin wood production, linked to the environmental pressures of cultivation and forest management, as well as the high demand for thermal and electrical power required for initial mechanical processing.

Likewise, in agreement with Klitou et al. [38], the drying phase of wet residue (SCGs) is identified as a major technology hotspot due to the biomass's high initial moisture content and its intrinsic susceptibility to biodegradation, which necessitates an immediate energy penalty. A key logistical factor in amplifying our impacts lies in the geographical boundaries of the system: whilst the reference authors restricted the biomass supply radius to a distance of 100 km [38,39], the logistical model in this study was extended to a 250 km radius, proportionally increasing the contribution of road transport in the categories of fossil resource depletion and greenhouse gas emissions.

To contextualize the sustainability of the proposed W10 formulation within the current European market, the results were compared with inventories reported for the ENplus-certified commercial wood pellet industry. In Spain, previous sectoral data reported by Scherhauser et al. [82] indicate that the production of 1 t of conventional pellets (from pine sawdust and wood chips) generated a carbon footprint of between 946 and 1048 kg CO₂ eq when conventional fossil fuel-based energy carriers (fuel oil and diesel) were used. This carbon footprint was reduced to a range of 752–853 kg CO₂ eq through the use of natural gas-fired combined heat and power (CHP) systems, and falls dramatically to 104–205 kg CO₂ eq when CHP plants based on bio-waste (such as animal fats) are integrated. Compared to these scenarios, the W10 pellets assessed in this study (468.20 kg CO₂ eq/t) demonstrate a clear competitive advantage over commercial wood pellets produced using non-renewable fossil fuel energy sources, achieving a reduction in environmental impact of between 37% and 55%.

This gap clearly defines the areas of potential optimization and eco-design for scaling up the process. Klitou et al. [38] demonstrated that by reducing reliance on the conventional electricity grid (specifically the Cyprus grid) through the integration of a passive solar drying system for the SCGs (accounting for 60.3% of thermal consumption) and a photovoltaic supply for the pelletization (37.9%) and cooling (1.7%), it is feasible to reduce the carbon footprint from 250 kg to 75 kg CO₂ eq per tonne (a reduction of around 70%).

Alternatively, the environmental performance of the proposed biofuel could be substantially optimized if the manufacturing infrastructure were located in regions with highly decarbonized national electricity grids or through local circular economy models, similar to those described by Bruins and Kwast in the Netherlands for “Streekpellets” (wood pellets from landscaping materials). These authors reported an impact of just 60 kg CO₂ eq/t, with pelletization and forest chipping accounting for 56% and 19% of the electricity-related impact, respectively, whilst the felling (4%), chip transport (9%), grading/drying (2%) and final distribution (10%) stages reflect an extremely efficient logistics chain. This performance is comparable to the German model, where the direct recovery of sawmill waste generates an impact of 73.60 kg CO₂ eq/t due to the zero allocation of primary forestry cultivation loads [82]. Consequently, the integration of on-site renewable energy and the reduction in the logistics collection radius are projected to be the most effective strategies for reducing the emissions from the optimized SCGs formulation and consolidating its position in the market for low-emission solid biofuels.

3.4. Logistics Sensitivity Analysis and Industrial Scalability

Although the laboratory results are highly favorable, the industrial scalability of wood and coffee pellets faces critical bottlenecks: the setup of reverse logistics for collection, and the energy intensity associated with biomass processing. To assess the system's robustness in the face of these operational variables, a sensitivity analysis was conducted based on modeling boundary or “worst-case scenarios”. This methodological concern is shared in the recent scientific literature; Svedovs et al. [39], for example, emphasize the importance of formally evaluating the influence of transportation loads on the ecological footprint,

positing this analysis as a mandatory focus for future developments in the optimization of solid biofuels.

Meanwhile, Klitou et al. [38] assessed the impact of logistics variability by applying a 20% parametric fluctuation to the SCGs transport distance, starting from a baseline scenario of 100 km. Their findings revealed a direct linear correlation between the supply radius and the environmental load: reducing the distance to 80 km lowered the (normalized) climate change indicator to a factor of 0.89, while increasing it to 120 km raised that factor to 1.00 (compared to 0.94 in the 100 km baseline scenario). However, the most significant finding by Klitou et al. is that 60.3% of the global life-cycle impacts are linked to the thermal and electrical demand of the drying stage of the SCGs. This prompted a comparative interregional analysis evaluating the influence of different energy mixes (grid mixes) in Europe. When modeling the electric drying process under high-carbon grid mixes such as those in Central and Eastern Europe (Poland) and Southern Europe (Greece), it was determined that drying contributes 41.33% and 37.64% to the total climate change impact, respectively. In contrast, the simulation using a decarbonized grid mix, such as that of Northern Europe (Sweden), drastically reduced this contribution to 5.03%. This marked divergence highlights that the decarbonization of the electricity sector and investment in on-site renewable energy generation are priority strategies for mitigating the life-cycle impacts of SCGs pelletizing plants.

It is imperative to note that the certainty of the conclusions of an LCA focused on industrial scaling depends strictly on the representativeness and reliability of the Life Cycle Inventory (LCI) data. Due to the intrinsic nature and volume of SCGs generation, meeting the continuous demand of a production line operating at commercial capacity requires expanding the geographic radius from which the raw material is sourced. In this context, a distance of 100 km represents a reasonable intermediate logistical scenario for sector-based collection. Conversely, simulation models that restrict the transport radius to markedly shorter distances—such as the 38.69 km scenario proposed by Rajabi S. et al. [69], which reports an environmental impact of 0.55 mPt/MJ—may lack practical representativeness in large-scale market scenarios. Such a logistics configuration would only be viable under the assumption of exceptionally high urban generation density or massive centralization of the waste. In commercial reality, coffee grounds are generated in a highly dispersed and fragmented manner (in the household and hospitality sectors), which establishes geographic dispersion as the primary logistical challenge for the recovery of this waste and justifies the need to use extended and realistic transport distances in sensitivity analyses.

Even though the baseline inventory for this study was modeled under an idealized proximity scheme (Km 0), reference scenario, a preliminary sensitivity analysis was conducted using the ReCiPe 2016 method to assess the system's robustness in the face of logistical constraints associated with the collection of SCGs. The results indicate that the net environmental benefit of the optimal formulation (W10) remains viable compared with the baseline scenario (W00, 35.94 Pt) up to a maximum catchment radius of 380.63 km (scenario 1), using the standardized transport process Transport, freight, lorry 7.5–16 metric ton, EURO6 for the simulation.

Based on the results summarized in Table 14, it can be seen that the integration of transport loads associated with coffee waste results in an average increase in the overall environmental impact of the formulations evaluated. Specifically, when comparing the profiles with the baseline scenario (which excludes transport), increases of 2.40% (W05), 4.83% (W10), 7.28% (W15), 9.71% (W20) and 12.13% (W25) compared with the baseline scenario without transport. This finding demonstrates that, even under a medium-distance distributed urban collection model, the use of SCGs maintains a solid competitive advan-

tage over the exclusive use of conventional forest biomass, whose supply chain typically involves longer cumulative distances and energy-intensive primary processing.

Table 14. Comparative environmental impact analysis of pellet formulations in different scenarios (UF: 1 t), using: ReCiPe 2016 and IPCC 2013.

Method	ReCiPe 2016 Endpoint (H) V1.03/World (2010) H/A				IPCC 2013 GWP 100a			
Evaluation	Reference Scenario ¹ [Pt]	Scenario 1 ² [Pt]	Scenario 2 ³ [Pt]	Scenario 3 ⁴ [Pt]	Reference Scenario ¹ [kg CO ₂ eq]	Scenario 1 ² [kg CO ₂ eq]	Scenario 2 ³ [kg CO ₂ eq]	Scenario 3 ⁴ [kg CO ₂ eq]
W00	35.94	35.94	36.09	36.09	480.47	480.47	483.40	483.40
W05	35.07	35.94	35.29	36.16	474.32	501.15	478.46	505.28
W10	34.20	35.94	34.48	36.23	468.20	521.85	473.54	527.19
W15	33.33	35.95	33.68	36.30	462.06	542.54	468.61	549.09
W20	32.47	35.96	32.88	36.37	455.92	563.24	463.67	570.99
W25	31.60	35.96	32.07	36.44	449.79	583.93	458.74	592.88

¹ Reference Scenario: Assessment of environmental damage in pellet production, simulation based on LCI. ² Scenario 1: Analysis of the influence of SCGs transport (380.63 Km). ³ Scenario 2: Analysis of the effect of the 10% increase in electricity consumption during pelletization. ⁴ Scenario 3: Analysis of the combined effect of SCGs transport (395.29 Km) and a 10% increase in electricity consumption during pelletization.

However, the sensitivity analysis identifies that emissions of fine particulate matter and nitrogen oxides (NO_x) resulting from urban transportation for the collection of coffee waste represent the main environmental trade-off. Therefore, to safeguard and maximize the sustainability of W10 pellets on an industrial scale, the logistics planning for SCGs collection must be strategically designed to mitigate or replace the transport of virgin and recycled wood fractions, whose current transport distances are 250 km and 239.65 km, respectively. Route optimization through local consolidation centers or the integration of low-emission transport fleets are emerging as necessary solutions to ensure the viability of this urban circular economy model.

On the other hand, when assessing the system's performance under a pessimistic scenario of energy inefficiency involving a 10% increase in electricity consumption during the densification stage (scenario 2), the overall environmental impact of W10 showed a marginal decrease of 2.04% in the total carbon footprint compared with formulation W00. However, when comparing this result with the standard inventory for the same blend, a 1.12% increase was identified, resulting in a displacement in emissions from 468.19 to 473.53 kg CO₂ eq per tonne of pellets produced.

Finally, a third scenario modelled the synergistic and concurrent influence of the system's two critical factors: the SCGs transport load and the 10% increase in electricity consumption. Under these boundary conditions, the optimal formulation W10 achieved a carbon footprint of 527.19 kg of CO₂ eq/t, which represents a net increase of 9.05% in emissions compared with the base blend W0. This result confirms the critical importance of avoiding the simultaneous convergence of operational and logistical inefficiencies.

As a mitigation strategy, it proposes decentralizing the processing scheme by establishing intermediate collection and conditioning centers for SCGs. At these local facilities,

situated within a radius of no more than 75 km of the selective collection system, the coffee waste would be pre-treated using thermal or passive solar drying. This scheme would enable the pre-dried biomass to be subsequently transferred to the central plant for pelletisation under highly energy-efficient conditions. This decentralized configuration ensures that the intrinsic environmental benefits of the co-designed pellet demonstrate structural robustness and do not depend on minor fluctuations or statistical inaccuracies arising from secondary inventory data in the Ecoinvent database.

4. Limitations and Future Prospects

Unlike the existing scientific literature on the LCA of SCGs pellets, where the assessment is purely theoretical and omits key empirical variables such as mechanical durability [38], this study experimentally validates the technical feasibility of SCGs densification prior to its environmental modelling. Given that SCGs compromise the structural cohesion of the biofuel and that the production of pellets made from 100% SCGs is technically unfeasible, their application is strictly limited to co-pelletization with woody matrices [83]. In this research, this limitation was overcome through eco-design and the experimental characterization of blends, identifying an optimal formulation (W10) that strictly complies with the criteria of the ISO 17225-6 [58] standard for its potential industrial scale-up.

Regarding the environmental profile, the incorporation of SCGs consistently reduces overall environmental impact compared with the reference scenario consisting only of wood (W00). Although the absolute carbon footprint of W10 (468.20 kg CO₂ eq/t) exceeds that reported in some simulations in the literature, a sector-specific analysis demonstrates high competitiveness in the real market. The official emission factors from the Spanish Office for Climate Change (OECC) for commercial wood pellets stand at 2025 kg CO₂ eq/t [84]. Within this framework, the W10 formulation ranks favorably within the first quartile for carbon intensity, establishing itself as a competitive, low-emission energy source.

To maximize the decarbonization of the biofuel and address the identified hotspots, the following eco-design guidelines are proposed for future research:

- Total lignocellulosic substitution: Replace 20% of virgin wood currently used with by-products from 100% recycled wood, thereby eliminating the upstream impacts associated with land use and forestry.
- Decarbonization of the energy mix: Simulate self-sufficiency through on-site renewable sources (solar photovoltaics or thermal biomass for drying), reducing reliance on the conventional electricity grid during critical stages of the process.
- Optimization of reverse logistics: Design geometrically optimized selective collection models for SCGs that reduce the transport radius, thereby directly decreasing the impact on the categories of human toxicity and fine particulate matter formation.

5. Conclusions

This study comprehensively evaluated the technical feasibility and environmental performance of a solid biomass pellet biofuel that incorporates SCGs into a matrix composed primarily of recycled wood (80% post-consumer wood and 20% virgin wood). Based on the experimental characterization conducted in accordance with ISO 17225-1 [3] standard and a “cradle-to-gate” life cycle assessment (LCA) at the factory level using the ReCiPe 2016 Endpoint methodology, the following conclusions can be drawn:

- Thermochemical and mechanical optimization: The incorporation of SCGs acts as an energy enhancer, causing the net calorific value to increase from 18.16 MJ/kg (control sample, W00) to 18.26 MJ/kg (25% SCG, W25). Conversely, a structural trade-off was observed in the form of a linear decrease in mechanical durability, which fell from 96.5% (W00) to 93.2% (W25). Within this performance spectrum,

the formulations incorporating 5% (W05) and 10% (W10) SCGs successfully meet the structural thresholds ($\geq 96.0\%$) required for non-wood Class B pellets according to ISO 17225-6 [58], achieving an optimal balance between mechanical stability and thermal density.

- **Ash Reduction and Operational Advantages:** A key technical advantage of incorporating SCGs is the systematic reduction in ash content as the proportion of agro-industrial residue increases. All blended formulations (W05 to W25) recorded ash content values between 1.75% and 2.19%, consistently falling well below the maximum threshold of 6.0% required by ISO 17225-6 [58]. This performance allowed all pellets to be successfully classified as Class A in terms of ash properties within the non-wood biomass categories. This reduction implies a lower risk of slag and scale formation, which improves performance and lowers maintenance costs for domestic and industrial heating systems.
- **Reduction in the environmental footprint:** Within the boundaries of the “cradle-to-gate” system under analysis, the increase in SCGs concentration demonstrates a significant and linear environmental benefit, reducing total environmental damage from 35.94 Pt (W00) to 31.60 Pt (W25), which constitutes a net ecological savings of 12.07%, and for the optimal mixture (W10), an ecological saving of 4.83%. This optimization is due to the allocation method (allocation, cut-off by classification), which classifies SCGs and recycled wood as “load-free” waste at the system boundary input, demonstrating that industrial symbiosis is an effective mechanism for mitigating the impacts associated with the exploitation of primary forest resources.
- **Environmental hotspots and robustness via sensitivity analysis:** The final damage profile is primarily concentrated in the human health macro-category, specifically driven by the indicators Global Warming-Human Health and fine particulate matter formation, and in the ecosystems macro-category, by Land use. These hotspots are strongly influenced by the environmental impact associated with the cultivation and management of virgin timber, as well as the high energy requirements of processing and the long-distance transport logistics of the wood fractions (239.65–250 km).

In conclusion, the W10 formulation is a highly sustainable, technically viable, and scalable bioenergy alternative, performing favorably with respect to institutional biogenic emissions reference standards (such as those of the Spanish Office for Climate Change). However, its environmental and economic viability is intrinsically linked to the geographic scope of reverse logistics, requiring low-emission transportation networks or regional consolidation centers to mitigate the impact of waste transport. This is also due to the reduction in the use of virgin wood and the use of cleaner energy. The findings of this research demonstrate that coffee grounds (SCGs) offer a superior competitive advantage over traditional forest biomass, positioning them as a key strategic vector for thermal decarbonization in high-density metropolitan areas. Ultimately, this approach not only exemplifies the benefits of waste valorization and industrial symbiosis but also offers an operational and transferable pathway for compliance with the strict emission limits and environmental standards imposed by the European Union.

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Abbreviations

The following abbreviations are used in this manuscript:

A	Ash (% of mass on dry basis)
BD	Bulk density (kg/m ³ as received)
C	Fixed carbon (% of mass on dry basis)
Cl	Chlorine (% of mass on dry basis)
D	Diameter (mm)
DU	Mechanical durability (% of mass of pellets after testing)
F	Amount of fines (% of mass, <3.15 mm)
FU	Functional unit
GWP	Global warming potential
HHV	Higher heating value (MJ/kg)
L	Length (mm)
LHV	Lower heating value (MJ/kg)
LCA	Life Cycle Assessment
LCI	Life cycle inventory
M	Moisture content (% of mass as received)
N	Nitrogen (% of mass on dry basis)
Piw	Pine woody biomass
Pow	Poplar woody biomass
Q	Net calorific value (MJ/kg)
Rw	Mixture of used wood with and without chemical treatment
S	Sulfur (% of mass on dry basis)
SCGs	Spent coffee grounds
VM	Volatile matter (% of mass on dry basis)

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