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Toward Energy-Efficient Circular Economy Systems: Process Integration and Industrial Symbiosis in the Agri-Food Sector

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Abstract

The transition towards circular production systems requires integrated methodologies capable of combining heterogeneous recovery technologies while providing consistent criteria for process evaluation and industrial implementation. This work presents a methodology, combining direct experimental measurement at laboratory and pilot scale with engineering-based estimation and industrial-scale projection, for the design and assessment of integrated circular valorisation processes, exploiting industrial symbiosis between agri-food residues and multilayer plastic waste streams. The proposed framework encompasses target product identification, recovery process definition, integration into representative case studies, experimental evaluation, mass and energy assessment, Key Performance Indicator (KPI) generation, and engineering-based industrial scale-up. Seven representative case studies were developed within the Agro2Circular project, covering the recovery of high-value bio-based products from agri-food residues and the recycling and biotransformation of multilayer plastic waste. Experimental data from laboratory- and pilot-scale prototypes were used to quantify material throughput, resource consumption, and process performance and to derive harmonised, industrially projected KPIs. The results show that mechanical and separation-based operations achieve substantial energy reductions upon scale-up, whereas biochemical and thermal conversion routes—particularly enzymatic depolymerisation and fermentation-based processes—remain the dominant energy contributors even under industrial conditions, indicating that process intensification, rather than scale alone, is required to close this gap. Beyond the specific case studies analysed, the framework constitutes a transferable methodology for the development, evaluation and scale-up of future circular valorisation platforms involving multiple waste streams and complementary recovery technologies.

Keywords: process integration; agrifood waste valorisation; mass and energy balance; process systems engineering; industrial symbiosis; energy key performance indicators; circular economy

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1. Introduction

The agri-food sector is undergoing a profound transition towards circular production models aimed at reducing resource consumption, minimising waste generation, and promoting the recovery of valuable materials from residual streams [1,2]. Alongside primary food processing activities, large volumes of polymer-based packaging waste and organic by-products are generated across agri-food value chains, creating significant environmental and energy-related challenges [3]. Recoverable waste streams include those generated

through the pre-market rejection of horticultural products, namely fruits and vegetables (FVH). Recent studies have shown that this rejection entails a significant environmental burden associated with the waste of water and energy resources and the related emissions generated during production, thereby revealing substantial inefficiencies within agri-food systems [4]. Traditionally, rejected FVH products have been managed through a range of approaches, extending from waste reduction and value recovery within the supply chain to valorisation in biorefineries and energy production. These strategies are based on circular economy principles, with particular emphasis on waste separation and sorting, the extraction of bioactive compounds, and the production of biogas and biofertilisers. Several studies have indicated that reduction and recovery strategies can decrease both environmental and economic impacts [5–8].

Recent advances in circular bioeconomy strategies increasingly emphasise the valorisation of these heterogeneous streams through integrated recycling and biotransformation routes, enabling the recovery of chemical building blocks, functional compounds, and biodegradable materials rather than solely focusing on waste disposal or energy recovery pathways [9,10]. Within this context, enzymatic extraction, microbial fermentation, reactive polymer processing, and advanced physical separation technologies have emerged as key procedures for closing material loops and supporting the development of sustainable agro-industrial systems [9]. These transformation routes frequently involve multi-stage processing chains combining pretreatment, separation, conversion, and downstream purification steps, which introduce additional operational complexity and variability in resource consumption. This results in heterogeneous processing environments with highly variable energy and resource demands across the different stages. Each stage may involve electricity, thermal energy, water, compressed air, refrigeration, agitation, pumping, or other auxiliary services. As a result, the environmental and technical feasibility of a valorisation pathway cannot be assessed exclusively through product yield or recovery efficiency. Its energy demand must also be quantified at the level of individual unit operations and across the complete processing chain [11,12].

In parallel with the growing adoption of circular processing strategies, global plastic production has experienced exponential growth over recent decades, exceeding 400 million tonnes annually and relying heavily on fossil resources as both feedstock and process energy [13,14]. The production of widely used polymers such as polyethylene, polypropylene, and polystyrene typically requires 70–80 MJ per kilogram of material, while more complex polymers may exceed 100 MJ/kg, highlighting the high energy intensity associated with virgin polymer manufacturing and reinforcing the importance of efficient recycling and valorisation pathways [15]. Despite these challenges, only a limited fraction of plastics has been effectively recycled [16], emphasising the need for improved process configurations capable of reducing energy demand and enhancing material circularity. Within agri-food packaging applications, multilayer structures and contamination issues further complicate recycling operations, requiring advanced sorting, delamination, and compatibilisation strategies to enable efficient material recovery [17]. Although these treatments can enable the recovery of valuable secondary materials, they may also introduce considerable electricity and thermal-energy requirements. The net value of the recycling pathway therefore depends strongly on its process configuration, operating conditions, recovery yield, throughput, and energy consumption.

Plastic recycling technologies have evolved towards increasingly diverse processing routes, including mechanical, dissolution-based, and chemical recycling strategies, each characterised by distinct operational requirements and energy consumption profiles [17]. Mechanical recycling remains the most industrially mature approach, although repeated processing may lead to material degradation and reduced product quality, while dissolution

and chemical recycling enable the recovery of higher-value intermediates from complex and multilayer materials [17,18].

In parallel, biotransformation processes based on enzymatic extraction, microbial conversion, and fermentation are gaining increasing attention within agri-food circular systems, enabling the recovery of bioactive compounds, biodegradable polymers, and chemical intermediates from organic residues [9]. Their energy requirements differ markedly from those of plastic-processing technologies because they may involve long residence times, controlled temperatures, aeration, agitation, sterilisation, downstream concentration, or low-throughput batch operation [19,20].

This technological heterogeneity makes direct comparison between processes particularly challenging. Absolute electricity consumption alone does not provide sufficient information because it is influenced by the quantity processed, experimental duration, production yield, equipment utilisation, and scale of operation [12,20–23]. Energy consumption must therefore be related to meaningful process outputs, such as the mass of waste treated, the mass of intermediate material recovered, or the quantity of final product obtained. In addition, the boundaries of the analysis must be clearly established to determine whether auxiliary systems, pretreatment stages, cleaning operations, heating, cooling, and downstream purification are included.

From a Process Systems Engineering perspective, considerable efforts have been devoted to improving the performance of individual unit operations through process optimisation and process intensification strategies [24]. However, this optimisation must be extended beyond individual processes to encompass interconnected recovery pathways capable of maximising resource efficiency throughout the entire waste-valorisation process [25]. Accordingly, recent studies have highlighted the need for system-level analysis frameworks capable of accounting for the interactions between multiple process units, infrastructure, auxiliary systems and operating conditions to identify meaningful efficiency improvements [18,26–28].

This system-level perspective is closely related to the concept of industrial symbiosis, whereby the by-products, residual streams, or intermediate outputs of one process are exchanged and valorised as inputs to another process, generating resource-efficiency gains that cannot be achieved by optimising individual processes in isolation [28]. Within circular bioeconomy platforms, industrial symbiosis becomes particularly relevant when heterogeneous waste streams—such as agri-food residues and multilayer plastic waste—are processed within a shared industrial ecosystem, since intermediate products obtained from one recovery pathway (e.g., chemical building blocks released during plastic depolymerisation) may serve as feedstock for complementary biotransformation routes. Recent reviews have further highlighted the transition from single-process valorisation towards integrated multi-feedstock and multi-product platforms capable of maximising resource efficiency through cascading recovery pathways [29,30]. In particular, integrated agri-food biorefineries have been proposed to combine complementary conversion technologies for the sequential recovery of multiple value-added products from organic residues [30], while recent studies emphasise that feedstock diversification, technology integration, process evaluation and industrial scale-up are essential to improve the technical and economic feasibility of future valorisation systems [29].

To the best of the authors' knowledge, comprehensive methodologies combining the recovery of high-value bio-based products from agri-food residues with the recycling and biotransformation of multilayer plastic waste within a single, symbiotically interconnected circular valorisation platform have not yet been reported. Furthermore, systematic frameworks encompassing target-product identification, recovery-process integration, experimental energy assessment, harmonised indicator calculation, and engineering-based

industrial-scale projection across such heterogeneous and interconnected recovery pathways remain scarce.

Within this context, the experimental characterisation of energy and resource consumption constitutes an essential component of process evaluation. Measurements conducted during process operation make it possible to determine the consumption associated with individual equipment and processing stages, identify the principal energy-demanding operations, and relate energy use to process duration, throughput, and production results. This information is especially important when several technologies with different operating principles and processing capacities must be integrated.

Energy-related Key Performance Indicators (KPIs) have been developed to translate energy and production data into interpretable measures of process performance [31,32]. From a value-chain perspective, energy indicators can be used to assess the consumption associated with different stages of plastic recycling and to relate this consumption to the quantity of material or product obtained [32]. At the equipment and production-system level, energy-related KPIs also support the identification of cause–effect relationships between manufacturing conditions, operating states, and energy demand [32,33]. Process-level monitoring can additionally be used to distinguish the energy consumed during productive and non-productive operating states. Depending on the characteristics of the equipment and production system, these states may include active processing, start-up, idle operation, maintenance, and downtime conditions. This distinction is relevant because the total consumption measured during an experimental test may include energy uses that are not directly associated with material transformation. Consequently, process assessment should consider both the total energy consumed and the operating conditions under which this consumption occurs.

By integrating energy and water consumption data into structured evaluation frameworks, KPI-based approaches facilitate continuous improvement and support data-driven decision-making in complex process environments [34–36]. In heterogeneous circular platforms, where unit operations range from biological reactors to extrusion-based processing lines, the use of harmonised indicators becomes particularly relevant to ensure consistent benchmarking across technologies. However, the application of such monitoring strategies to heterogeneous processes within the agri-food sector remains limited.

To address this gap, this work presents an integrated methodology for the systematic design and evaluation of circular valorisation platforms for agri-food residues and multilayer plastic waste, in which industrial symbiosis is achieved through the exchange of intermediate streams and by-products between complementary recovery pathways, and process performance is quantified through the calculation of harmonised KPIs representative of industrial-scale operation. The proposed framework spans the complete development process, from target-product identification and recovery-process selection to process integration, experimental evaluation, mass and energy assessment, KPI calculation, and engineering-based industrial scale-up.

The novelty of this work lies in treating agri-food and plastic-waste valorisation not as independent recovery routes but as a symbiotically interconnected system evaluated on a common, harmonised basis—an integration that, to the authors' knowledge, has not previously been demonstrated experimentally or projected to industrial scale. Specifically, the objectives of this study are (i) to define representative recovery processes and integrate them into interconnected case studies exploiting synergies between both waste streams; (ii) to experimentally quantify mass and energy balances for each recovery technology at laboratory and pilot scale; (iii) to derive harmonised, technology-independent KPIs enabling direct comparison between heterogeneous unit operations; and (iv) to project these KPIs to representative industrial-scale operating conditions through engineering-based scale-up,

thereby assessing the technical feasibility of the integrated platform. The methodology is demonstrated through representative case studies developed within the Agro2Circular project [37,38], providing a transferable framework for evaluating heterogeneous recovery technologies and supporting the implementation of circular production systems. While individual processes were analysed and key performance indicators (KPIs) were calculated within the scope of the project, the testing scales were not unified to estimate cumulative resource consumption within an integrated industrial chain, nor was the overall scalability potential systematically modelled. By combining experimentally measured consumption data, material-flow analysis, harmonised performance indicators, and engineering-based industrial projection, the proposed framework provides a transferable approach for estimating the resource requirements of heterogeneous recovery technologies, supporting the design of technically feasible and resource-efficient circular production systems. Beyond this methodological contribution, this work also quantifies, for three of the recovery pathways studied, the resource-displacement benefit relative to the equivalent virgin-material or primary-production reference systems that they are intended to replace, as detailed in Section 3.6.

2. Materials and Methods

2.1. Overall Methodological Framework

Building on the target products and representative case studies defined for the Agro2Circular project (Sections 3.1–3.3), an integrated valorisation process was designed for the recovery of high-value products from fruit and vegetable residues and multilayer plastic films generated in the agri-food value chain. The design followed the methodological framework shown in Figure 1, which combines process integration analysis, experimental evaluation, mass and energy assessment, and scale-up analysis. Specifically, this study utilises the empirical results obtained throughout the project, meaning that the data presented for the different testing scales directly correspond to those evaluated in the prototypes developed within Agro2Circular.

This methodology was structured into four consecutive stages, ranging from the technical characterisation of the recovery processes tested within the Agro2Circular project to the estimation of their performance at industrial scale.

First, a technical assessment of the recovery processes developed and tested within the Agro2Circular project was carried out. This stage included the identification of the technologies used and the characterisation of their main operating conditions.

For each process, several aspects were analysed, including the required operating times, the nominal and effective capacity of the equipment, the different treatment stages, material flows and throughputs, and the associated operational requirements. This characterisation made it possible to define the boundaries of each process and to identify the information required for the subsequent stages of the assessment.

The experimental evaluation was then conducted through the operation of the prototypes developed within the Agro2Circular project. The equipment was operated under representative conditions in order to obtain experimental data on its performance, treatment capacity and operational behaviour.

The main operating variables were recorded during the tests, thereby generating experimental datasets for each technology. These datasets formed the quantitative basis of the study and included information on material inputs and outputs, operating times, electricity and thermal energy consumption, water consumption, and process yields.

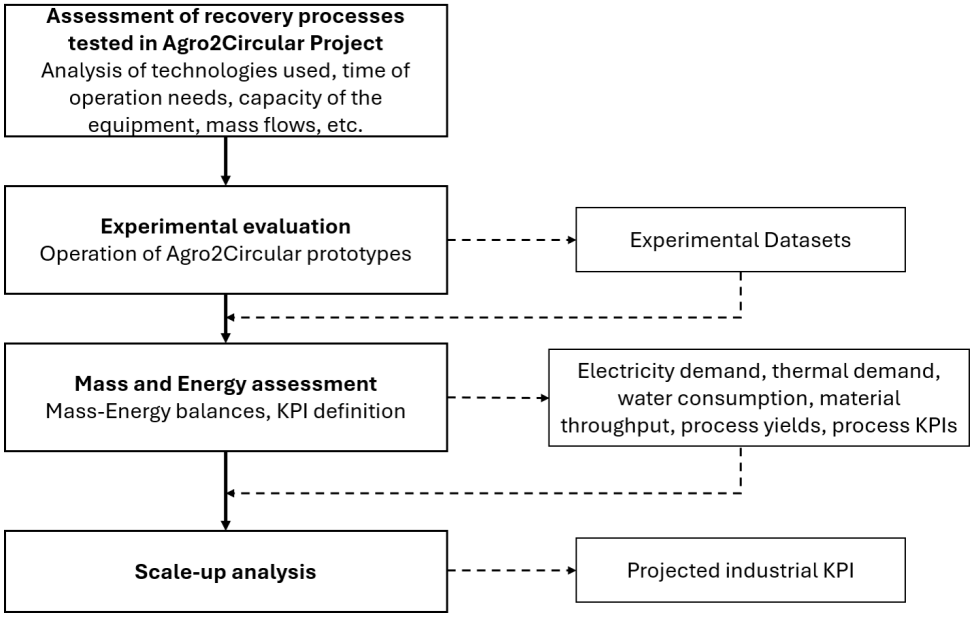


Figure 1. Methodological framework followed for the design of an integrated valorisation process for the recovery of high-value products from fruit and vegetable residues and multilayer plastic films generated in the agri-food value chain. Solid arrows indicate the sequential order of the main methodological stages; dashed arrows indicate the information (datasets or results) generated by each stage and used as input for the subsequent stage.

Based on the experimental data, mass and energy balances were developed for each process. The mass balances were used to quantify the amounts of material fed, processed, recovered, rejected or lost, while the energy balances were used to determine the electricity and thermal energy requirements associated with equipment operation.

At this stage, indicators such as electricity demand, thermal energy demand, amount of material processed or recovery rate, and process yield were calculated.

The definition of the KPIs enabled the different technologies to be compared on a common basis and allowed both their technical efficiency and their use of energy and material resources to be assessed.

Finally, a scale-up analysis was conducted using the results obtained during the experimental evaluation as a starting point. The analysis considered the capacity of the prototypes, operating times, material throughputs, specific resource consumption and the yields achieved by each of the technologies assessed.

The scale-up was not approached solely as a proportional extrapolation of equipment capacity. The nature and specific characteristics of each process were also taken into account, together with the availability on the market of equivalent equipment with higher processing capacities and its suitability for the requirements of each case study.

Where commercially available equipment was capable of meeting the required treatment capacity, its use was assessed by considering both its nominal capacity and its expected performance. However, the use of larger-capacity equipment was not automatically regarded as the most appropriate option, as an increase in equipment capacity did not necessarily result in improved process yield, energy efficiency or recovered-product quality.

As an alternative, the implementation of several process units or production lines operating in parallel was evaluated. This configuration makes it possible to increase the overall production or processing rate while maintaining constant operating conditions and a uniform processing rate throughout the overall process or over the period considered in the case study. This approach also provides greater operational flexibility, facilitates

adaptation to variations in feed flow and reduces the effect of the shutdown of a single unit on the overall operation of the facility.

On the basis of these considerations, the KPIs were projected to industrial scale, including estimated electricity, thermal energy and water requirements, treatment capacity, production of recovered materials and expected process yields. The scale-up was therefore performed through a combination of experimental-data extrapolation, assessment of commercially available technologies and definition of the most appropriate equipment configuration for each process.

Finally, for clarity throughout this document, four terms are used to qualify the origin of the reported values and are applied consistently in the text, tables (including Table A1) and figures of this manuscript: (i) measured values are those obtained directly from calibrated on-site instrumentation during the experimental operation of the laboratory- and pilot-scale prototypes (Section 2.2); (ii) calculated values are derived from measured primary data through the mass and energy balance equations and KPI definitions described in Section 2.3 and therefore remain tied to the experimentally tested scale; (iii) estimated values are those obtained, in the absence of direct on-site measurement, either from partner-supplied consumption data combined with equipment technical/manufacturer specifications (Section 2.2), or from process-specific engineering calculations based on first-principles energy balances and equipment performance assumptions (Section 3.5); and (iv) projected values are the industrial-scale KPIs presented in Section 3.5, obtained by extrapolating the measured/calculated experimental KPIs to a representative industrial operating scale through a combination of data extrapolation, technology assessment and engineering-based scale-up assumptions. Projected values have not been validated through actual operation at industrial scale and should therefore be interpreted as engineering estimates of expected performance rather than as directly measured quantities; this distinction is discussed further in the limitations presented in Section 3.7.

2.2. Experimental Data and Performance Variables

The operational datasets obtained from the experimental evaluation of the defined case studies constituted the basis for the performance assessment presented in this work. The datasets were generated during the operation of laboratory- and pilot-scale prototypes developed within the Agro2Circular project, representing the recovery technologies integrated into the proposed circular valorisation platform.

Electrical power and energy consumption were measured using network/power-quality analysers installed on-site by the authors' team, using the same instrument model across all directly monitored tests, with the exception of the microwave-assisted extraction unit, for which the power analyser integrated into the equipment itself was used. All measuring instruments hold a calibration certificate issued by an accredited calibration body. Network/power-quality analysers compliant with IEC 61557-12 [39] (power mettering and monitoring devices for AC power quality), IEC 62053-22 [40] and IEC 62053-23 [41] (static meters for active and reactive energy) and the power-quality measurement methods defined in IEC 61000-4-7 [42], IEC 61000-4-15 [43] and IEC 61000-4-30 [44] (Ed. 2); the electrical safety and electromagnetic compatibility of the measurement equipment complied with IEC/UL 61010-1 [45] (Ed. 3) and EN 61326-1:2013 [46]. According to the manufacturer's technical specifications, the combined measurement accuracy of the instrumentation was ±2.0% of the reading plus ±0.13% associated with the resolution of the data acquisition, resulting from the accuracy of the measurement probes (±1.0%), the current transformers (±0.5%) and the voltage transformers (±0.5%). Given the reduced number of experimental campaigns available for each process (see Section 3.7), this instrument-level accuracy

was not further propagated into a formal uncertainty budget for the reported KPIs; this is discussed as a limitation of the present study.

Data were logged at 1 s intervals for processes with operation times on the order of hours and at 1 min intervals for processes with operation times on the order of days. For prototypes operated at partner facilities where on-site monitoring was not feasible, the corresponding partner provided the total energy consumption or the average operating power together with the operating time; in these cases, the reported consumption was estimated by combining the partner-supplied measurements with the equipment's technical/manufacturer data. Each process was evaluated in a single experimental run; consequently, no replicate-based variability could be quantified, which is acknowledged as a limitation of the present dataset (see Section 3.7). Reported operating times correspond to the active processing period, from start-up to shutdown, and do not include cleaning or maintenance downtime.

The collected datasets comprised information on material inputs and outputs, intermediate streams, product yields, residual fractions, water consumption, electrical energy demand and thermal energy demand. These variables were recorded for each recovery process and subsequently organised according to the corresponding case study, providing a consistent dataset for the integrated assessment of the proposed valorisation pathways. Particular attention was given to electrical and thermal energy demand, which were considered separately due to their distinct roles within the recovery processes and their different contributions to the overall process performance.

The experimental datasets described in this section constituted the input information for the mass and energy assessment methodology presented in Section 2.3, where they were used to quantify material and energy flows and derive the performance indicators employed for the evaluation of the proposed integrated circular valorisation platform.

2.3. Mass and Energy Assessment and KPI Calculation

The experimental datasets described in Section 2.2 were processed through a common mass and energy assessment methodology to enable the consistent evaluation of the proposed case studies. Since each case study comprises one or more interconnected recovery processes, the assessment was first performed for each individual recovery process and subsequently integrated according to the corresponding case-study configuration. As the analysed recovery technologies operated under different processing scales, flow rates, operating continuity and levels of process integration, the assessment considered both the measured operational values and the corresponding operating conditions. This common methodological framework enabled meaningful comparisons between heterogeneous recovery technologies while preserving the characteristics of each experimental system.

For each recovery process, a mass–energy balance was established using the corresponding experimental datasets. The balances included the quantification of raw material inputs, processing capacity, operating time, electrical and thermal energy consumption, product outputs, residual streams and process yields. These process-level balances provided a harmonised description of the operational performance of each recovery technology and served as the basis for calculating the corresponding KPIs.

The resulting process-specific KPIs were subsequently integrated according to the configuration of each case study, providing a consistent basis for evaluating both the performance of the individual recovery technologies and the overall system-level performance of the proposed valorisation pathways. To ensure consistency across the heterogeneous unit operations analysed in this work, KPIs were expressed using one of four functional units, depending on the nature of each process and the stage of the value chain being assessed: kWh per kg of feedstock entering the overall case study; kWh per kg of material fed to the

specific unit operation; kWh per kg of final product obtained; or kWh per litre of working reactor volume, used for fermentation and other liquid-phase biological processes. For enhanced traceability, Appendix A provides a table (Table A1) reporting the KPIs of the different process stages, referred to the material input of that stage, of the process, and of the case study.

2.4. Process Scale-Up and Industrial Energy Assessment

The experimentally determined KPIs constituted the input information for the subsequent scale-up assessment presented in Section 3.5. During this stage, the KPIs obtained from the experimental mass and energy assessment were extrapolated to representative industrial operating conditions to estimate the expected energy performance of the proposed recovery technologies. The scale-up assessment focused on the evolution of specific energy consumption (kWh kg^{-1}), while preserving the experimentally determined material balances and process yields. This approach enabled the evaluation of the integrated valorisation pathways under industrial throughput conditions while maintaining the process performance established through direct experimental measurement at laboratory and pilot scale.

The scale-up methodology combined experimentally determined KPIs with process-specific engineering assumptions representative of continuous industrial operation. Depending on the characteristics of each recovery process, the extrapolation considered the expected reduction of laboratory-scale limitations, including improved equipment utilisation, reduced contribution of fixed and idle energy demands, lower thermal losses associated with more favourable surface-to-volume ratios, and improved energy integration under steady-state operation.

Different scale-up strategies were applied according to the nature of recovery technologies. Mechanical and physical separation processes were assumed to benefit primarily from classical engineering scale effects, resulting in a progressive reduction in specific energy consumption as production capacity increased. In contrast, biochemical and thermochemical processes involving long residence times, batch operation or low throughput conditions required additional engineering considerations related to process intensification, including increased solids loading, continuous or semi-continuous operation, improved reactor design, and enhanced heat and mass transfer.

Whenever representative experimental energy data were unavailable, or laboratory-scale operation introduced energy penalties that were not representative of industrial conditions, the corresponding process KPIs were estimated through process-specific engineering calculations based on first-principles energy balances and equipment performance assumptions. Depending on the characteristics of each recovery process, these calculations considered thermal energy requirements, heat losses, and additional electrical energy contributions associated with process equipment (e.g., vacuum systems, mixers, cooling units, or auxiliary equipment). The corresponding equations, engineering assumptions, and parameter values adopted for these calculations are presented together with the relevant Case Studies in the Results, Section 3.5.

3. Results and Discussion

3.1. Target Product Definition and Circular Economy Requirements

The analysis of agricultural and agri-food waste streams enabled the identification of several target compounds with high valorisation potential. Table 1 summarises the selected compounds together with their corresponding feedstock sources and potential applications. These findings constitute the basis for defining the recovery processes described in Section 3.2.

Table 1. List of products that can be obtained.

Typology	Component	Application
Organic waste	Organic fibres	Used in the production of biocomposites, biodegradable textiles, and the paper industry.
	Dietary fibres	Used as a functional ingredient and technological additive in the food, nutraceutical and animal feed industries.
	Phenolic compounds	Used in the production of antioxidants, natural preservatives, and in the pharmaceutical and cosmetic industries.
	Carotenoids	Employed in the production of nutritional supplements, natural colorants, and products for eye and skin health.
	Juices with high sugar content	Used for bioethanol production, in the food industry, or as natural sweeteners.
	Dry biomass	Used in the production of biofuels as a renewable energy source and in heat generation.
	Pellets	Used in renewable energy generation, as biofuel in stoves and industrial boilers.
	PHBV (Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) bioplastics)	Used in the production of biodegradable products, packaging, and sustainable product components.
Multilayer plastics	Pure aluminium	Used in the production of packaging, electronic products, automotive components, and in the packaging industry due to its light weight and corrosion resistance.
	Aluminium masterbatch	Employed to enhance the properties of aluminium in the production of packaging products, increasing durability, resistance, and visual properties.
	PE (Polyethylene)	Used in the production of packaging, bags, bottles, and in cable insulation applications due to its versatility and resistance.
	PET (Polyethylene Terephthalate)	Used in the production of plastic bottles, textiles, food and beverage containers, as well as in automotive components manufacturing.
	EG (Ethylene glycol)	Employed in plastic manufacturing, antifreeze production, textile industry as synthetic fibre, and in resin manufacturing.
	TPA (Terephthalic acid)	Primarily used in the production of PET plastic bottles, textiles, and recyclable packaging products.
	PCA (Protocatechuic acid)	Used in cosmetics, pharmaceuticals as a stabiliser, and in cleaning products due to its ability to retain water and form gels.
	Biomass	Used for the production of biofuels and renewable energy, as well as in the manufacture of bioplastics and other biodegradable products.
	Microbial oils	Used for biofuel production, in the food industry as edible oils and nutritional supplements, as well as in cosmetics.

3.2. Definition of the Processes

Based on the target products identified in Section 3.1, two main recovery process categories were defined: (I) green hybrid extraction, purification, and stabilisation routes for the recovery of high-value bioactive compounds from agri-food residues, and (II) integrated recycling and biotransformation routes for the valorisation of multilayer plastic waste. The transversal recovery processes composing these routes are described below, including their main operational stages, associated equipment, and process flow diagrams.

Throughout Figures 2–12, green-outlined boxes consistently indicate the recovered or final products of each process, whereas orange-outlined boxes indicate secondary by-product streams. In the category-level overview diagrams (Figures 2 and 7), black-outlined boxes represent the individual transversal processes, whereas in the individual process flow diagrams (Figures 3–6 and 8–12), blue-filled boxes represent the specific unit operations composing each process. An arrow branching into two distinct paths indicates the separation of the process stream into two output fractions, while two operations enclosed within the same bounding frame and connected by a double-headed arrow indicate that both are carried out within the same combined unit operation. Small labelled arrows (e.g., "water") represent auxiliary utility inputs or outputs associated with a given stage, rather than the main process-flow stream.

3.2.1. Category (I): Green Hybrid Extraction, Purification, and Stabilisation Routes Aimed at Recovering High-Value Bioactive Compounds from Agri-Food Residues

The industrial processes involved in the upcycling of agrifood waste are outlined in the diagram in Figure 2. Within this category, four processes were identified: Process (1), green hybrid technologies for the extraction of bioactive substances from agri-food wastes; Process (2), the development of new food, nutraceutical, and cosmetic formulations based on extracts derived from agri-food residues; Process (9), biological valorisation based on haloarchaea cell factories for the production of Poly(3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV) bioplastics and C-50 carotenoids; and Process (10), development of high-barrier polymer compounds through compatibilisation strategies and extensional flow mixing during extrusion.

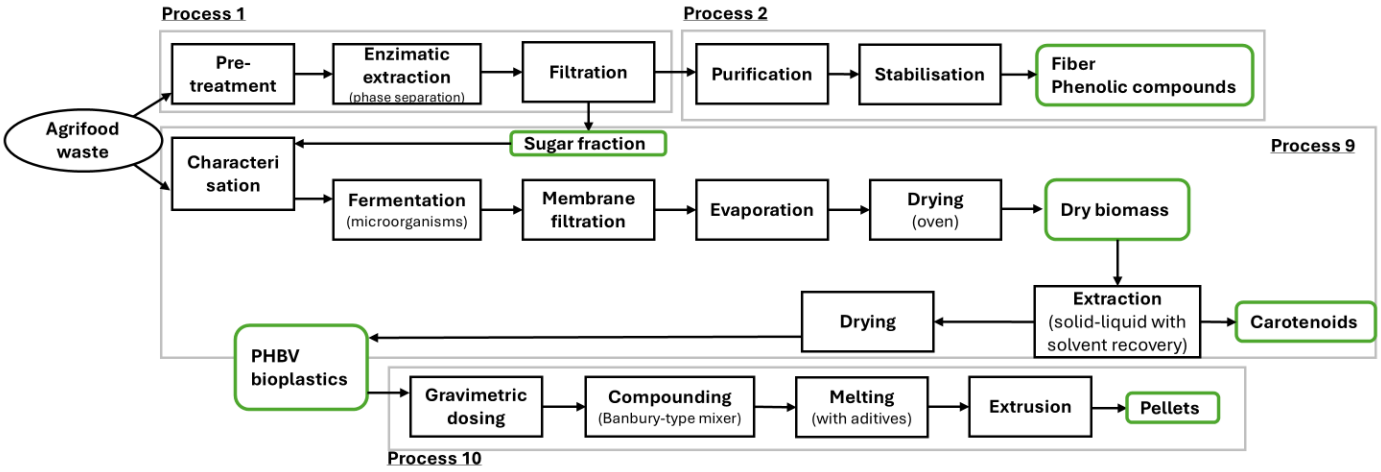


Figure 2. Processes identified in Category (I).

Process (1), illustrated in Figure 3, represents the initial stage within the upgrading pathway of fruit and vegetable by-products. This process involves the recovery of bioactive compounds from diverse residues (seeds, skin, peels, leaves, etc.) generated during fruit and vegetable processing, including citrus, apples, grapes, artichoke, cauliflower, and broccoli [47]. The biomass is first subjected to pretreatment operations, including washing and size reduction, to improve the efficiency of the subsequent extraction step. Bioactive compounds are then released through enzymatic treatment, followed by phase separation by filtration, generating a solid fraction and a liquid fraction. These intermediate streams constitute the feedstock for the alternative downstream processing routes (Processes 2a and 2b), where the target products are purified and stabilised.

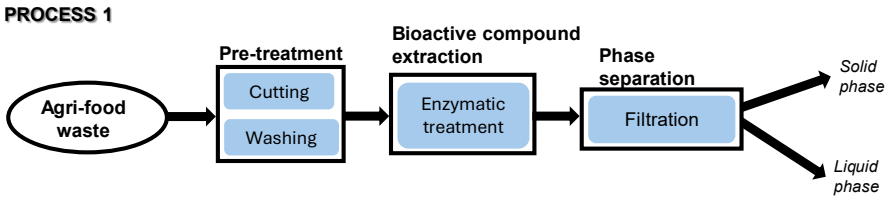


Figure 3. Flow diagram of Process 1.

Process (2), illustrated in Figure 4, comprises the downstream purification, concentration, and stabilisation of the solid and liquid fractions generated in Process (1) to obtain stable, high-value products. Two alternative technological configurations are defined. In Process 2a, the solid fraction is purified by washing and stabilised by dehydration to produce a fibre-rich extract. In parallel, the liquid fraction is concentrated by membrane filtration and purified through adsorption/desorption using resins, followed by lyophilisation to obtain a phenolic extract [48]. The sugar-rich eluate generated during the desorption step is subsequently concentrated to produce a sugar-rich by-product. In Process 2b, the solid fraction undergoes microwave-assisted extraction followed by resin-based purification and dehydration to obtain the fibre-rich extract, whereas the liquid fraction is concentrated by ultrafiltration and stabilised by dehydration to produce the phenolic extract. Both configurations target the same final products while employing different downstream purification, concentration, and stabilisation technologies.

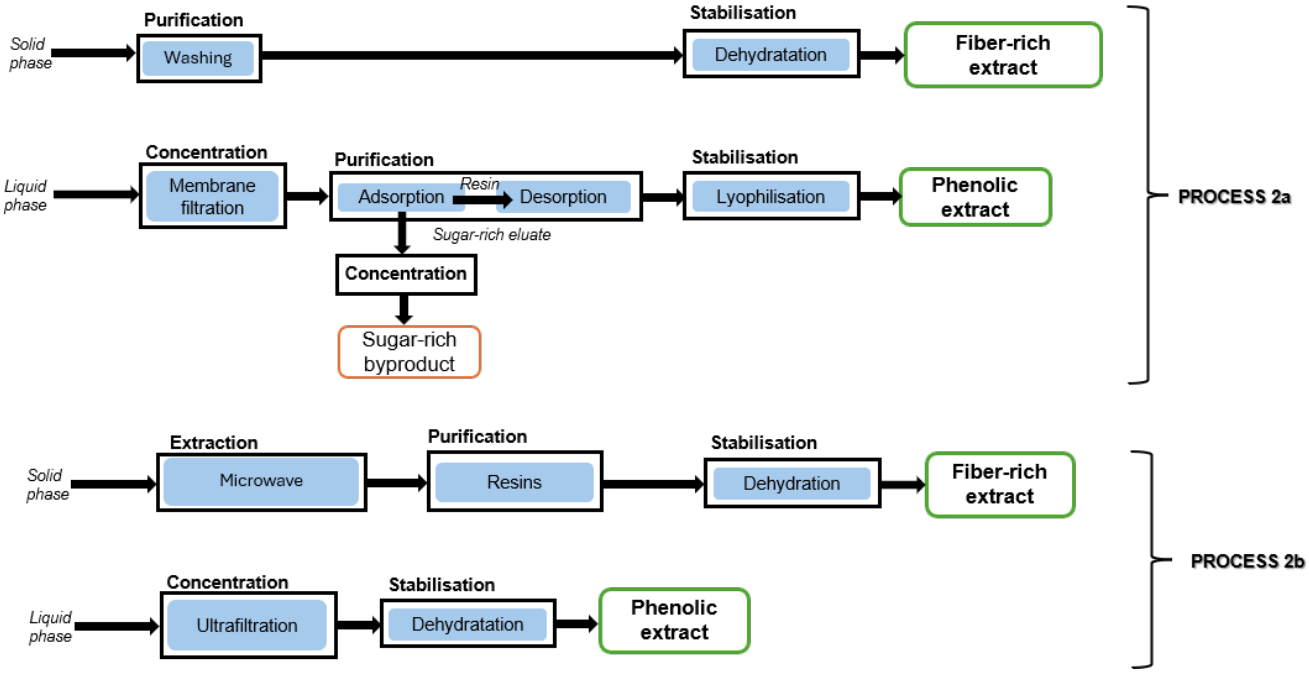


Figure 4. Flow diagram of Processes 2a and 2b.

Process (9) describes the production of PHBV and carotenoids through a biotechnological route based on the valorisation of organic waste streams, as illustrated in Figure 5. The process begins with the aerobic fermentation of a mixture comprising organic waste fractions (e.g., lemon residues), biomass, and non-converted TPA residuals used as an external carbon source, which may originate from industrial by-products such as residual sugars generated during the extraction of polyphenols from organic waste [49,50]. The fermentation is carried out using *Haloferax mediterranei*, leading to the formation of biomass containing PHBV and carotenoids [51]. Following fermentation, the biomass is subjected

to a concentration step, typically involving tangential flow filtration and subsequent evaporation. The concentrated biomass is then subjected to a selective green solvent extraction process [52], generating a PHBV-rich solid fraction and a carotenoid-rich liquid fraction. The solvent is subsequently recovered and recycled within the process, while the PHBV-rich fraction is dried to obtain the final polymer product.

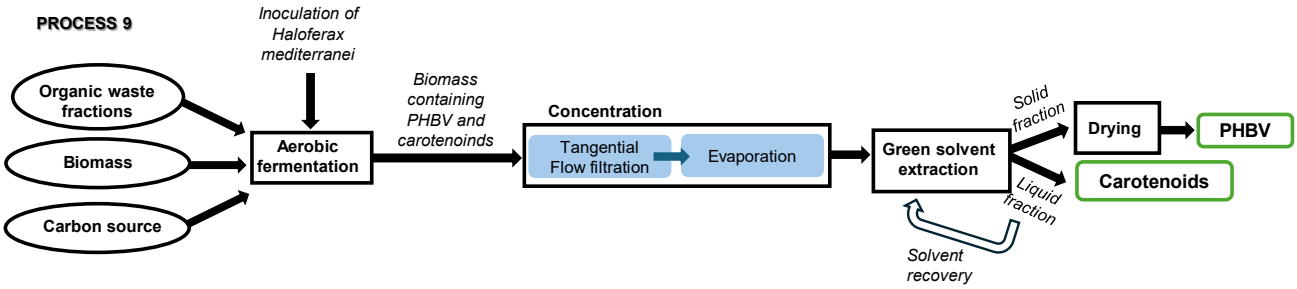


Figure 5. Flow diagram of Process 9.

Process (10) comprises the production of biodegradable plastic films and packaging materials from PHBV-based formulations through a sequence of compounding, extrusion, and transformation steps, as illustrated in Figure 6. Initially, the raw material is pneumatically conveyed into a feeding hopper, from which it is transferred to a compounding chamber, specifically a Banbury-type internal mixer. Within this unit, the formulation undergoes both dispersive and distributive mixing, ensuring proper homogenisation of the different components. During this stage, suitable additives are incorporated to enhance processability and tailor the final material properties. The resulting homogeneous mass is subsequently fed into an extrusion system, where it is melted and shaped. At the end of the extrusion stage, the material is cut and pelletised to produce biodegradable pellets as an intermediate product. These pellets are then supplied to downstream converters, where they are processed using conventional film-forming technologies (e.g., blown or cast extrusion) to obtain final products such as biodegradable agricultural mulch films or bioplastic-based food packaging materials.

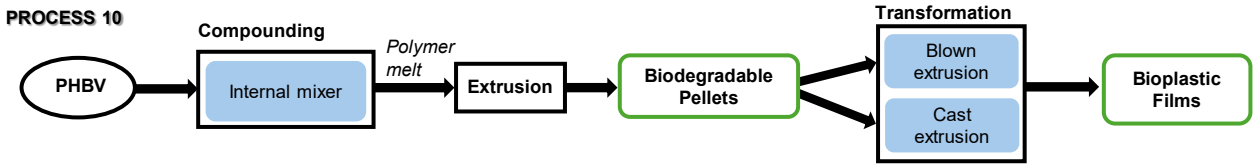


Figure 6. Flow diagram of Process 10.

3.2.2. Category (II): Integrated Recycling and Biotransformation Pathways Combining Sorting, Physical De-Lamination, Enzymatic Depolymerisation, Decontamination, and Mechanical Recycling Strategies for Multilayer Plastic Valorisation, Together with Extensional Flow Mixing Approaches for the Upcycling of Recycled Multilayer Materials

This category comprises an integrated recovery scheme consisting of six transversal recycling and biotransformation processes developed to obtain the target products identified in Section 3.1 (Figure 7). The proposed configuration combines physical separation, mechanical recycling, enzymatic depolymerisation, and biotechnological conversion routes for the valorisation of multilayer plastic waste, enabling the recovery of high-value materials, chemical building blocks, and bio-based products. The six processes composing the proposed recovery pathway are described below.

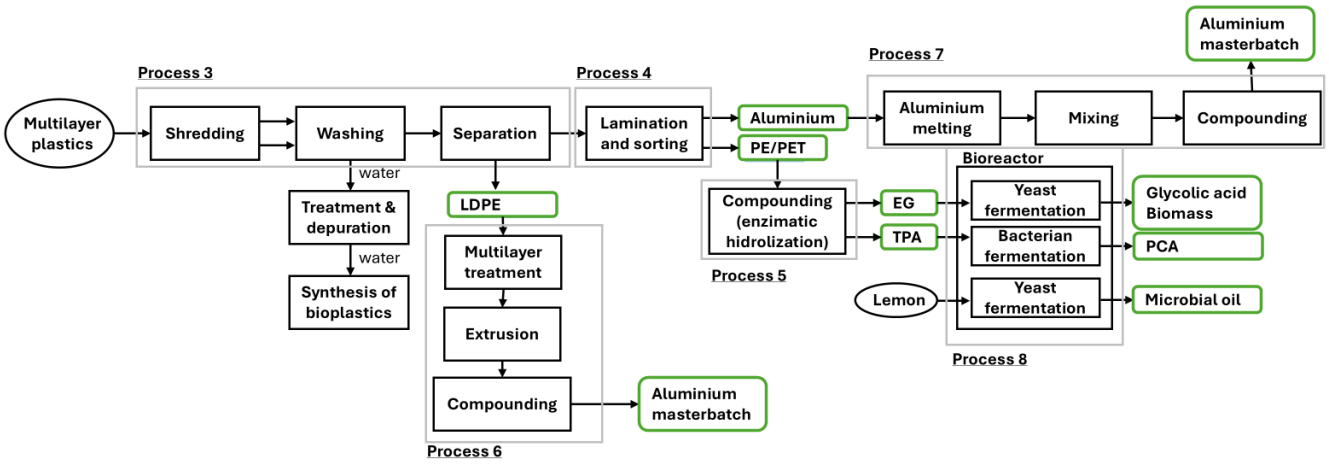


Figure 7. Processes identified in Category (II).

Process (3) corresponds to the combined pretreatment, preliminary decontamination, and optical sorting stage applied to multilayer plastic materials derived from agri-food packaging and agricultural films (Figure 8). The objective of this process is to convert heterogeneous multilayer waste streams into compositionally distinct fractions through mechanical conditioning and sensor-based classification technologies. The incoming feedstock first undergoes pretreatment operations, including shredding to reduce particle size, washing to remove organic residues and contaminants, and subsequent centrifugation and drying to decrease moisture content and stabilise material handling conditions. These operations ensure consistent material flow and improve detection accuracy during the sorting stage. After pretreatment, the material stream is processed through a sensor-assisted optical sorting unit, where controlled illumination and automated detection enable the selective separation of multilayer structures. Based on structural composition and surface characteristics, the heterogeneous input stream is primarily divided into two main output streams: a metallised fraction and a non-metallised fraction. The metallised stream comprises aluminium-containing and metallised multilayer structures, whereas the non-metallised stream includes polyolefin-based multilayers and barrier materials without metallic layers.

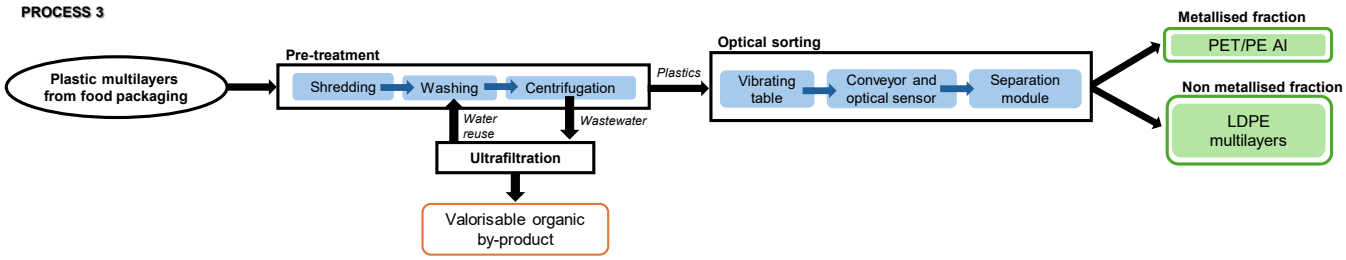


Figure 8. Flow diagram of Process 3.

Process (4) focuses on the physical separation of aluminium from complex multilayer plastic structures through delamination-based technologies. The input material corresponds to an aluminium-containing fraction that may originate from separation processes, such as those described in Process (3). The main objective of this stage is to isolate metallic and polymeric components from metallised multilayer materials, enabling the generation of compositionally distinct output streams. The incoming multilayer fractions undergo a delamination step in which the bonded layers are mechanically separated to disrupt the adhesion between aluminium and polymer layers. This operation is followed by a sorting stage that classifies the resulting materials according to their structural composition. As a re-

sult of this process, the multilayer structures are converted into two primary output streams: an aluminium-rich fraction and a polymeric fraction mainly composed of poly(ethylene terephthalate) (PET)- and polyethylene (PE)-based materials.

Process (5) describes the enzymatic depolymerisation of PET contained in multilayer PET/PE structures previously classified in Process (4), as depicted in Figure 9. The objective is to convert PET into its constituent monomers, terephthalic acid (TPA) and ethylene glycol (EG). The incoming waste stream is first subjected to a pre-treatment sequence comprising washing, extrusion, and granulation, yielding pretreated multilayer PET with enhanced accessibility for enzymatic action.

In parallel, PET-degrading enzymes (PET hydrolases) are produced via a dedicated biotechnological route involving plating, pre-culture, inoculum preparation, fermentation, cell harvesting, cell disruption, and centrifugation. The resulting enzymatic extract is subsequently applied to the pretreated material in an aqueous reaction system, where enzymatic depolymerisation takes place. As a result of this step, PET is partially converted into its monomers, EG and TPA, and enzymes are recovered. However, a fraction of the polymer is only depolymerised to the intermediate mono(2-hydroxyethyl) terephthalate (MHET), indicating incomplete hydrolysis. To achieve full conversion, the reaction mixture is subjected to an alkaline hydrolysis step through the addition of NaOH, promoting the complete transformation of MHET into EG and TPA. At this stage, both products are present in diluted aqueous form. Therefore, a phase separation step is required, which is achieved by acidification of the medium via HCl addition. This induces the precipitation of TPA, allowing its separation as a solid phase, while EG remains in the liquid phase and can be recovered by decantation.

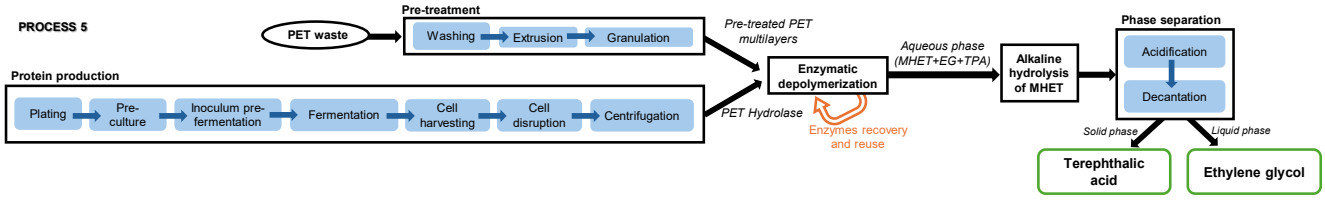


Figure 9. Flow diagram of Process 5.

Process (6), illustrated in the process flow diagram shown in Figure 10, represents the integrated treatment of low-density polyethylene (LDPE) multilayer materials previously obtained through upstream classification processes (e.g., Process 3). This process comprises plastics decontamination, reactive extrusion compounding, and subsequent transformation steps. The objective is to remove contaminants present in the multilayer plastic waste and to convert the purified material into value-added products.

The incoming LDPE multilayer stream first undergoes a water-based cleaning stage to eliminate solvent residues, soil particles, chemical traces, and organic contaminants. Following washing, the material is subjected to centrifugation to reduce moisture content and stabilise handling conditions, while mechanical grinding is performed to obtain multilayer particles within the required size range (20–30 mm). The final decontamination step consists of vacuum treatment, where volatile organic compounds (VOCs) and odorous substances are removed under reduced-pressure conditions to improve the quality of the recycled multilayer plastic stream.

The decontaminated material is subsequently processed through reactive extrusion, where compatibilisation and extensional flow mixing are applied to optimise blend morphology and interfacial interactions. The compounded material is then pelletised to obtain intermediate pellets. These pellets may either be commercialised as a final product or further transformed into plastic films through blown or cast extrusion technologies.

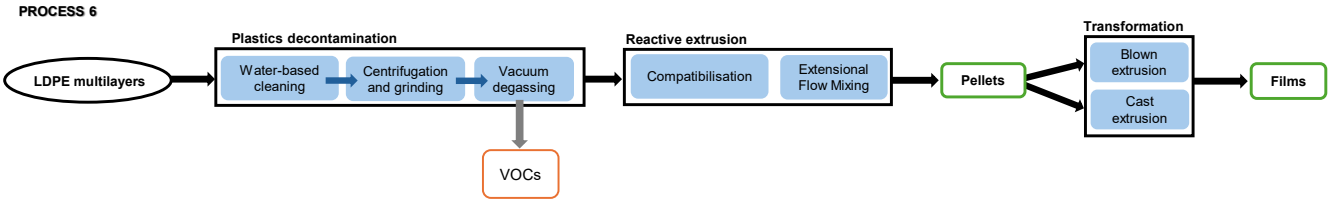


Figure 10. Flow diagram of Process 6.

Process (7) follows a procedure analogous to that described in Process (6), with the main distinction being the incorporation of aluminium powder recovered in Process (4), as illustrated in Figure 11. The objective of this process is to produce aluminium-filled polyethylene materials with enhanced functional properties. As in Process (6), LDPE-based multilayer waste undergoes decontamination and subsequent reactive extrusion, including compatibilisation and extensional flow mixing, to ensure proper dispersion of the different components. During extrusion, aluminium powder is introduced into the polymer matrix, and the desired proportion of each component can be automatically controlled, enabling precise adjustment of the final formulation. The incorporation of aluminium provides added functionalities to the resulting materials, such as improved thermal and electrical conductivity, enhanced barrier properties, and increased reflectivity. The latter is particularly relevant for applications such as agricultural shading films, where control of light transmission is required. The resulting composite pellets are subsequently processed into films via conventional techniques, including blown or cast extrusion.

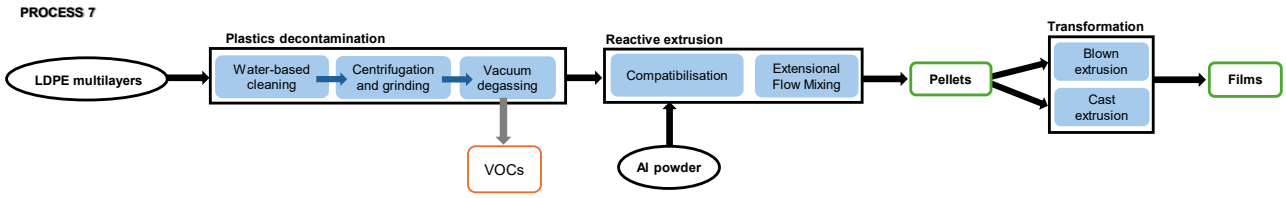


Figure 11. Flow diagram of Process 7.

Process (8) represents the biotechnological upcycling stage applied to enzymatic degradation products generated in Process (5), TPA and EG, together with enzymatically treated agri-food residues obtained through routes analogous to Process (1) (Figure 12). The objective of this process is to convert these intermediates into high-value biochemical building blocks through dedicated microbial biotransformation pathways. For each input stream, a specific conversion strategy is implemented. EG undergoes a bioconversion route enabling its transformation into glycolic acid (GA) [53,54], while TPA is biologically converted into protocatechuic acid (PCA) through bacterial biotransformation. In parallel, enzymatically treated agri-food residues—such as citrus-derived substrates used as representative examples—can be processed through sterilisation, fermentation, centrifugation, and solvent evaporation stages to obtain microbiological oils. These biotransformation pathways typically involve aerated bioreactor systems supported by auxiliary operations such as sterilisation, temperature control, agitation, centrifugation, and vacuum-assisted evaporation. As a result of Process (8), plastic-derived intermediates and agri-food residues are biologically upgraded into value-added compounds such as glycolic acid, protocatechuic acid, and microbiological oil, contributing to the integrated circular valorisation strategy of the system.

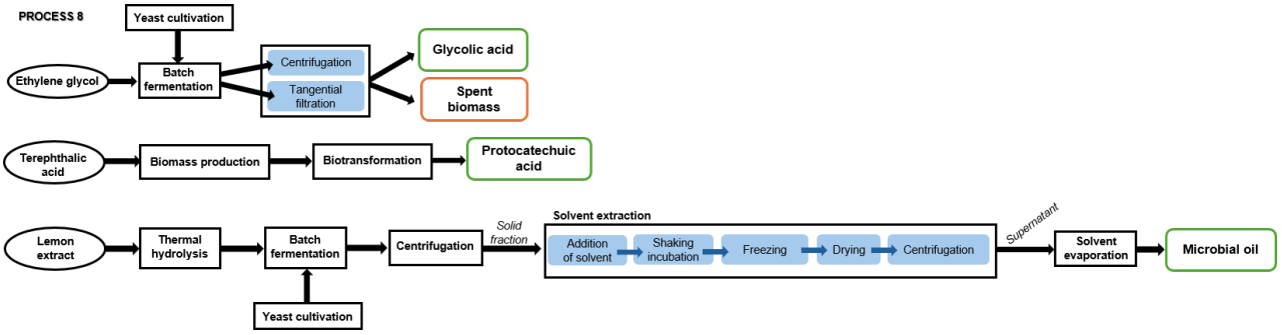


Figure 12. Flow diagram of Process 8.

3.3. Process Integration and Case Study Development

Based on the recovery processes defined in Section 3.2, seven representative case studies were developed to represent the different valorisation pathways within the proposed integrated platform. Table 2 summarises the relationship between the identified recovery processes and the corresponding case studies.

Table 2. Relationship between Transversal Processes and the Analysed Case Studies. Note: Data correspond to the specific scales (laboratory or pilot) at which each process was experimentally tested.

Process	Description	Case Study	Scale
1	Green hybrid technologies for extraction of bioactive substances from agrifood wastes	3, 4	Route 1: Extraction 100 kg/h and purification 15 kg Route 2: Extraction 50 kg/h and purification 15 kg
2	New food, nutraceuticals & cosmetic formulations using extracts from agrifood wastes	3, 4	Delivery systems up to 1 kg
3	Identification and sorting of multilayer materials	1	Multilayers sorting flow rates of 25 kg/h
4	Separation of aluminium (Al) from complex multilayer structures	1	Pilot plant up to 20 kg batches
5	PET/PE enzymatic depolymerisation	1	1 kg/h laboratory scale
6	Plastics decontamination	7	1000 L/day of wastewater filtered and 500 kg of plastics decontamination
7	Aluminium recycling and chemical modification	7	Up to 1 kg
8	Upcycling of enzymatic degradation products (TPA, EG) by cell factories	2	Up to 30 L
9	PHBV and C-50 carotenoids development by Haloferax mediterranei haloarchaea cell factory	5	Up to 100 L and extraction process to 1–3 L
10	High barrier compounds by extensional flow mixing and compatibilisation	6	Up to 1000 kg of capacity

The interrelation between the different recovery processes, as well as the case studies through which they are articulated, is illustrated in Figure 13. The integration of the recovery processes reveals two main valorisation pathways combining plastic recycling and agri-food valorisation strategies. Case Studies 1, 6 and 7 form the plastic recycling pathway, whereas Case Studies 3–5 constitute the agri-food valorisation pathway. Case Study 2 acts as the interface between both pathways by integrating intermediates derived from plastic recycling and agri-food residues. Together, these interconnected case studies form a common circular

valorisation platform that maximises resource recovery through the sequential utilisation of intermediate material streams.

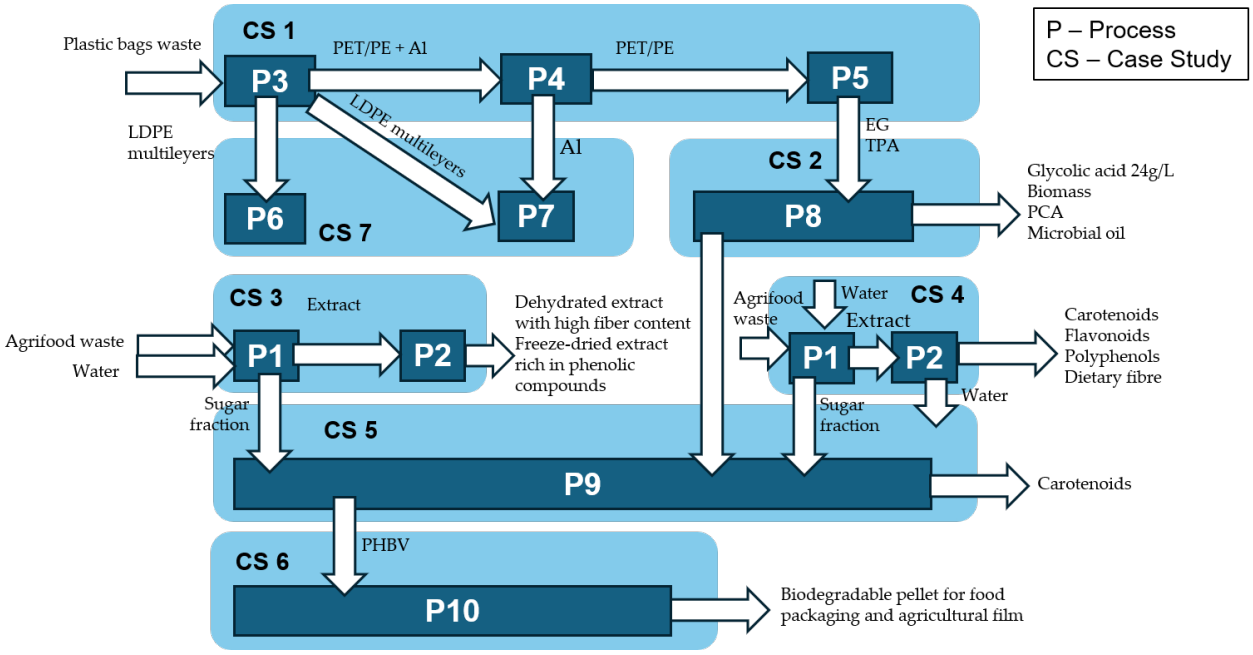


Figure 13. Interrelation between the different processes and their associated case studies.

Case Study 1 integrates Processes 3, 4, and 5, using post-consumer multilayer plastic packaging waste as feedstock. The integrated process sequence comprises pretreatment, optical sorting, delamination, and enzymatic depolymerisation, yielding recovered LDPE multilayers together with TPA and EG as the main output streams.

Case Study 2 integrates intermediates originating from Case Study 1 together with enzymatically treated lemon peel from Case Study 3. Case Study 2 addresses biotransformation processes (Process 8) for the valorisation of these chemical intermediates and agro-industrial residues. The integrated biotransformation process yields GA, PCA, microbial oil and biomass as the main products.

Case Studies 3 and 4 integrate Process 1 with the alternative downstream configurations defined in Processes 2a and 2b, respectively. Both case studies use agri-food residues as feedstock and aim to recover fibre-rich and phenolic extracts through enzymatic extraction followed by purification, concentration, and stabilisation of the solid and liquid fractions. The two case studies differ only in the downstream processing technologies applied in Processes 2a and 2b, with Case Study 3 additionally recovering a sugar-rich by-product.

Case Study 5 centres on fermentation-based valorisation of residual streams. The experimental platform consists of a fermentation bioreactor, followed by filtration systems and drying units, enabling the production of PHBV bioplastics and carotenoid-rich products from organic substrates.

Case Study 6 integrates Process 10, using PHBV-based formulations as feedstock. The integrated process sequence comprises compounding, extrusion, pelletisation, and subsequent film-forming operations for the production of biodegradable plastic materials [55]. Biodegradable pellets are obtained as an intermediate product and further processed into biodegradable agricultural mulch films and bioplastic-based food packaging materials, which constitute the final output streams.

Case Study 7 integrates Processes 6 and 7, using the LDPE multilayer and aluminium fractions recovered in Case Study 1 as feedstocks. The integrated process sequence comprises decontamination, compatibilisation, conditioning, and extrusion operations for the

upgrading of the recovered materials. The main output streams are recycled LDPE multilayer materials and recycled aluminium, intended for subsequent food packaging and agricultural applications.

3.4. Experimental Analysis of the Case Studies

This section presents the experimental analysis of the seven case studies. For each case study, the mass balances, product yields, electrical and thermal energy consumption, and the corresponding KPIs are determined from the experimental datasets obtained at laboratory and pilot scale.

To support the traceability and consistency of the KPI values reported throughout this section, a complete process-by-process breakdown for every case study is provided in Table A1 (Appendix A), listing the scale tested, nominal electricity power, main inlet mass flow rate (or total mass processed), operating time, and energy consumption for each sub-process, together with the corresponding KPI calculated at three levels—the sub-process itself, referred to the input of the overall process, and the overall process—as well as the aggregated KPI of the case study. This allows the numerator and denominator underlying each reported KPI to be verified independently for every processing stage.

3.4.1. Case Study 1—Processes 3, 4, 5

Process 3 consists of two stages: pre-treatment and optical sorting, whose operating parameters, recovered outputs, and associated energy consumption are summarised in Table 3. Pre-treatment comprises shredding, washing with water recirculation, centrifugation, and drying, preparing the multilayer plastic for downstream separation. Washing and extrusion represent the main cooling-demanding operations due to the use of chilled water supplied by shared chillers. For the analysed throughput, pre-treatment constitutes a significant share of the overall energy demand, with consumption largely influenced by the level of plastic contamination. In the absence of monitoring data, pre-treatment energy demand was estimated based on a processing capacity of 25 kg/h. Optical sorting involves sensor systems, conveyor drives, vibration units, lighting modules, separation devices, and auxiliary cooling, resulting in a comparatively lower but non-negligible electrical load. However, during the experimental trials, the optical sorting unit did not achieve a reliable separation between the metallised and non-metallised fractions of the multilayer stream. Consequently, for the purposes of this case study, no aluminium-containing fraction was considered to be effectively separated at this stage, and the entire output flow was assumed to proceed directly to the delamination stage (Process 4) without prior fractionation.

Additionally, the pre-treatment stage requires a continuous air purification process to remove airborne particles generated by the dirt present on the plastic waste. During the experimental trial, the power demand of this system was estimated at 12.1 kW, corresponding to an additional 0.484 kWh/kg. However, this KPI is strongly penalised by the small scale at which the process was tested.

The delamination and adsorption-based separation process (Process 4) combines thermal activation, selective surface adsorption, and mechanically assisted interfacial failure to promote the separation of multilayer polymer structures. It counts with recirculation, agitation, and controlled heating which enhances mass transfer and promotes interfacial weakening between immiscible polymer layers, while the final drying/adsorption unit stabilises the separated fractions and removes residual moisture. This hybrid configuration enables an intensified separation pathway beyond conventional mechanical delamination approaches, as summarised in Table 4.

Table 3. Mass–energy balance of Process 3 (Case Study 1).

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Pre-treatment	Bags waste plastics 25 kg/h	8.9 kW	1 h	8.9 kWh	Recycling plastic 20 kg/h	Dirt/ contaminants removed—5 kg/h	0.3544 kWh/kg
Pre-treatment (air depuration)	Not Applicable	12.1 kW	1 h	12.1 kWh	-	-	0.4840 kWh/kg
Optical sorting	Recycling plastic 20 kg/h	14.4 kW	1 h	14.4 kWh	LDPE multilayers / PET/PE + Al (no aluminium fraction effectively separated)	-	0.2200 kWh/kg (referred to 25 kg/h of bags waste plastics)

Table 4. Mass–energy balance of delamination process (Process 4) in Case Study 1.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Delamination	1, Recycling plastic 20 kg/h	16.7 kW	1 h	16.7 kWh	LDPE multilayers / PET/PE + Al	-	0.67 kWh/kg (referred to 1200 kg of bags waste plastics)

In this case, the energy consumption KPI of the delamination stage was indexed to the inlet flow of Process 3, since Processes 3 and 4 are aligned within the same scale.

Process 5, which focuses on PET/PE depolymerisation, involves energy consumption mainly associated with pre-treatment operations, including extrusion, cutting, and cooling, which enhance enzymatic accessibility in downstream stages. Table 5 summarises the mass and energy balances of Process 5. In this case, since Process 5 was not tested on a scale aligned with the previous processes, the waste input that would have entered Process 3 was calculated assuming the same yield as tested.

Table 5. Mass–energy balances for PET/PE (Process 5) in Case Study 1.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Pre-treatment	PET/PE 1 kg/h	6 kW	1 h	6 kWh	Pre-treated PET/PE—0.99 kg	PET/PE not useful—0.01 kg	6.2 kWh/kg
Enzymatic degradation	PET—1 kg PET Hydrolase—3 g Na_2HPO_4—0.14 kg NaH_2PO_4—0.19 kg Wash water	0.5 kW	48 h	24 kWh	MHET—0.79 kg	PET (high crystallinity content)—0.21 kg	23.8 kWh/kg
MHET conversion	MHET—1 kg NaOH—4 g HCl—3.6 g	0.5 kW	3 h	1.5 kWh	TPA—0.79 kg EG—0.3 kg	None	1.5 kWh/kg

3.4.2. Case Study 2—Process 8

Table 6 summarises the electricity consumption of the main process units involved in Case Study 2, corresponding to the ethylene glycol conversion to biomass and glycolic acid

(first line), to the TPA conversion to PCA (second line), and to the yeast fermentation line for the lemon extract conversion to microbial oil (third line), respectively.

Table 6. Mass–energy balance of Process 8 (Case Study 2): Ethylene Glycol Conversion to Biomass and Glycolic Acid.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	KPI
Biomass and GA production	EG from demo 1 (3 L)	0.3 kW	7 days	53.1 kWh	GA and biomass—8 L	17.7 kWh/L
PCA production	TPA from demo 1 (1 L)	0.5 kW	5 days	62.7 kWh	PCA—4.3 g	62.7 kWh/L
Microbial oil production	Lemon extract from demo 3 (0.8 L)	0.5 kW (yeast fermentation) + 1.1 kW (rotavapor)	3 days + 8 h	44.1 kWh	Microbial oil—11.8 g	55.2 kWh/L

Being biological processes, the electrical power demand is relatively low. However, due to the extended reaction times, ranging from 2 to 7 days, the overall energy consumption is relatively high. This effect is particularly pronounced in the case of PCA and microbial oil production, as laboratory-scale experiments were performed using only 1 and 0.8 litres of input respectively, which amplifies the specific energy demand.

The observed electrical energy consumption in the fermentation processes is primarily associated with the requirements for aeration and temperature control. As these reactions are aerobic, continuous supply of oxygen via compressed air is necessary to sustain microbial metabolism and product formation. Additionally, the reactions are exothermic, generating heat that must be removed to maintain optimal fermentation temperatures, which entails energy consumption by cooling systems. Together, these operational demands account for the majority of the electricity usage, despite the inherently low power requirements of the fermenter and auxiliary equipment.

3.4.3. Case Study 3—Process 1 and 2a

The energy consumption associated with Case Study 3 is mainly linked to thermal and phase-change operations required for the extraction, purification, and stabilisation of bioactive compounds from agrifood residues. As shown in Table 7, Process 1, which comprises pre-treatment, enzymatic extraction, and purification stages, is dominated by the energy demand of the extraction step, largely due to the use of thermal energy supplied by natural gas for enzymatic processing. In contrast, electrical consumption associated with mechanical operations such as cutting, filtration, and agitation represents a minor contribution to the overall energy demand of this process.

Within Process 1, purification stages involving concentration and adsorption exhibit a moderate energy requirement, primarily associated with membrane filtration, while pre-treatment operations contribute marginally due to their short operating time. Overall, the energy profile of this process reflects the combined effect of thermal extraction and downstream separation steps at pilot scale.

Process 2a, focused on stabilisation of the extracted fractions, exhibits a significantly higher energy demand compared to upstream operations. As reported in Tables 8 and 9, dehydration and lyophilisation steps dominate the total electricity consumption, with lyophilisation being the most energy-intensive unit operation due to its prolonged operating time and the need to remove large amounts of water through phase change under vacuum conditions.

Table 7. Mass–energy balance of Process 1 (Case Study 3): Extraction of Bioactive Substances from Agri-food Wastes.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Pre-treatment	Agri-food waste processed—50 kg	1.7 kW	1 h	1.7 kWh	All material processed remains intact	-	0.0347 kWh/kg
Enzymatic extraction	Water—0.15 m^3 Agri-food waste—50 kg Enzyme—0.005 kg Water for boiler—0.19 m^3	0.8 kW_e + 88.7 kWh_{th}	107 min	1.4 kWh_e and 158.1 kWh_{th}	Agri-food waste—50 kg	-	0.03 kWh_e/kg 3.16 kWh_{th}/kg
Filtration	Agri-food waste—50 kg	0.7 kW	1 min	0.01 kWh	Liquid phase 150 L Solid phase 50 kg	-	0.0 kWh/kg

Table 8. Mass–energy balance of Process 2a (Case Study 3): New Food, Nutraceutical and Cosmetic Formulations Using Extracts from Agri-Food Wastes. Solid Phase Summary.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Purification (washing)	Agri-food waste—50 kg	0.8 kW_e + 85.4 kW_{th}	100 min	1.3 kWh_e + 142.3 kWh_{th}	Condensed water—0.08 m^3	-	0.03 kWh_e/kg 2.85 kWh_{th}/kg
Stabilisation (dehydration-oven)	Agri-food waste—40 kg	0.8 kW_e	48 h	38.4 kWh	Dehydrated fibre (>70%) —3.6 kg	Steam—36.4 kg	0.768 kWh_e/kg

Table 9. Mass–energy balance of Process 2a (Case Study 3): New Food, Nutraceutical and Cosmetic Formulations Using Extracts from Agri-Food Wastes. Liquid Phase Summary.

	Raw Materials Input	Power Demand	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Pre-concentration	Solid–liquid mixture 150 L Water 240 L	9.4 kW_e + 114.8 kW_{th}	30 min	4.7 kWh_e + 57.4 kWh_{th}	Pre-concentrated 150 L	-	0.09 kWh_e/kg 1.15 kWh_{th}/kg
Purification (resins)	Pre-concentrated 150 L	0.2 kW_e	180 min	0.6 kWh_e	Purified 150 L	-	0.012 kWh_e/kg
Concentration	Permeated by resins	0.0 kW	-	1.1 kWh_{th}	Sugar fraction 0.016 m^3/h	-	0.022 kWh_{th}/kg
Pre-concentration	Purified 150 L	0	-	0	20 L/80 kg	-	0
Stabilisation (Lyophilisation)	Agri-food waste—80 kg	1.1 kW_e	96 h	109.4 kWh	Dehydrated liquid extract—0.6 kg Evaporated water—79.4 kg	-	2.19 kWh_e/kg

These results indicate that, for Case Study 3, energy consumption is strongly driven by thermal management and water removal processes rather than by mechanical handling or separation steps. Consequently, optimisation efforts should primarily target dehydration and freeze-drying operations, which represent the main energy hotspots within the agrifood valorisation pathway.

3.4.4. Case Study 4—Process 1 and 2b

Case Study 4 comprises two sequential processes. Process 1 is aimed at treating the agri-food waste and separating it into a solid and a liquid phase, while Process 2 focuses on the treatment and stabilisation of the remaining solid and liquid phases. Tables 10 and 11 provide a summary of the main operating stages, material inputs and outputs, and associated energy consumption for both processes.

Table 10. Mass–energy balance of Process 1 (Case Study 4).

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Pre-treatment	Artichoke waste—100 kg Water—205 kg	Industrial cutter—1.3 kW	0.8 h	1.1 kWh	Washed and cutted artichoke—100 kg	-	0.01 kWh/kg
Enzymatic extraction	Washed and cutted artichoke—100 kg Water—300 kg Enzymes—10 mL Citric acid—0.1 kg	Agitator and boiler—0.4 kW_e + 15 kW_{th}	1 h	3 kWh	Antioxidants (solid phase)—100 kg Dietary fibers (liquid phase)—300 kg	-	0.004 kWh_e/kg + 0.15 kWh_{th}/kg
Manual filtration	Dietary fibers—310 kg	-	-	-	Dietary fibers (liquid phase)—300 kg and washed agrifood waste 10 kg	-	0 kWh/kg

Table 11. Mass–energy balance of Process 2b (Case Study 4). Solid Phase Summary.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Microwave extraction	Antioxidants (solid phase)—10 kg Water—40 kg Ethanol—60 kg	Microwave extractor—6 kW (4.7 kW nom.)	180 min	14.1 kWh	Solution of antioxidants—100 kg	Solid—10 kg	1.41 kWh/kg
Concentration + Purification	Solution of antioxidants—100 kg EtOH—5 kg Resin—0.2 kg	1.3 kW	100 h	125.4 kWh	Antioxidant extract—0.03 kg Resin—0.2 kg EtOH—5 kg Dietary fibres (liquid phase)—300 kg	Water—60 kg	1.25 kWh/kg

As shown in Table 10, the energy demand for Process 1 is mainly associated with extraction and phase-separation operations. It is observed that the primary consumption is thermal, due to the water heating requirements needed to achieve conditions that favour the enzymatic reaction.

For Process 2b, the overall energy demand is largely driven by downstream processing operations, as detailed separately for the liquid and solid phases in Tables 11 and 12, respectively. The purification of the solution of antioxidants is the dominant energy-consuming step in the solid phase, mainly due to the prolonged thermal treatment required for water removal. By contrast, the energy profile of the liquid phase is primarily affected by the oven separation process.

Table 12. Mass–energy balance of Process 2b (Case Study 4). Liquid Phase Summary.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Ultrafiltration	Dietary fibres (solid phase)—300 kg	5.9 kW	1 h	5.9 kWh	Solution of dietary fibres—30 kg	Solid—unknown	0.02 kWh/kg
Dehydration	Solution of dietary fibres—30 kg	Oven—4.8 kW	10–48 h	22.8 kWh	Solid enriched in dietary fibres—1.2 kg	Water vapour	0.76 kWh/kg

Overall, the energy analysis indicates that, in Case Study 4, extraction technologies and water-removal operations are the primary drivers of electricity consumption, whereas mechanical pre-treatment and auxiliary purification steps play a secondary role.

3.4.5. Case Study 5—Process 9

Tables 13 and 14 summarise the mass and energy balances of Case Study 5, covering fermentation, downstream processing, and the extraction and purification of PHBV. The overall energy profile of the process is largely dominated by biological conversion and subsequent biomass handling operations.

Table 13. Mass–energy balance of Process 9 (Case Study 5). Fermentation, Filtration and Drying.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
—	Salts—48.02 kg Nitrogen source—1.61 kg Carbon source—2.1 kg Phosphorous source—21 g NaOH—400 g HCl—1 kg	2.8 kW	65 h	184 kWh	Fermentation culture—200 L	Wash water—200 L	3.53 kWh/kg
Filtration	Fermentation culture—200 L	Tangential filtration—4 kW	24 h	96 kWh	Concentrated biomass—15 L Water brine—185 L	Wash water—50 L	0.32 kWh/L
Drying	Concentrated biomass—15 L	Oven—2.7 kW	48 h	129.6 kWh	Dried biomass—2 kg	None	3.24 kWh/L

Table 14. Mass–energy balance of Process 9 (Case Study 5). PHBV Extraction and Purification.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
PHBV extraction and purification	Biomass —13 kg	5.5 kW	All elements—1.5 h	Motor stirrer—0.8 kWh Heating jacket and heated oil unit—4.5 kWh Solvent vapor condenser unit—1.5 kWh Temperature control unit—1.5 kWh	PHVB—500 g Water brine	-	0.63 kWh/kg

Table 14 highlights that PHBV extraction and purification contribute a comparatively lower share to the overall energy demand when compared to upstream fermentation and

drying stages. The energy requirements of this step are primarily associated with heating and agitation during solvent-based extraction, while auxiliary units such as condensation and temperature control play a secondary role.

Regarding carotenoids extraction, this stage will take only a portion of the wet concentrate sent to the dehydration stage. It has a relatively high energy consumption of 78 kWh/L, mainly due to the high number of hours required in the incubator shaker and subsequently in the lyophiliser, totalling a full week, as detailed in Table 15.

Table 15. Mass–energy balance of Process 9 (Case Study 5). Carotenoids extraction.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Carotenoids extraction	Wet concentrate—2 L	Incubator shaker—0.5 kW Lyophiliser—2 kW	Incubator shaker—120 h Lyophiliser—48 h	156 kWh	Carotenoids	-	78 kWh/L

Overall, the results indicate that the energy performance of Case Study 5 is strongly influenced by time-intensive biological processes and thermal operations rather than by solvent-based purification stages. This suggests that optimisation strategies should prioritise fermentation efficiency, aeration management, and drying intensity to reduce the overall energy footprint of the process.

3.4.6. Case Study 6—Process 10

Case Study 6 is based on an extrusion and compounding process designed for the production of polymer pellets at pilot scale. As shown in Table 16, the energy demand of this demonstrator is associated with continuous mechanical and thermal operations, including material feeding, mixing, transportation, and polymer melting within the extruder.

Table 16. Mass–energy balance of Process 10 (Case Study 6): Total Energy Consumption.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Compounding and compatibilization	10 kg	35 kW	0.75 h	26.3 kWh	9.65 kg	-	2.63 kWh/kg

The results highlight that, in Case Study 6, energy consumption is mainly driven by installed power rather than by operating duration, emphasising the relevance of process continuity and throughput in determining the specific energy demand of extrusion-based valorisation routes.

3.4.7. Case Study 7—Processes 6 and 7

Case Study 7 presents an integrated configuration based on multilayer decontamination followed by downstream compatibilisation, extrusion, and material conditioning stages. Sharing a common pretreatment stage, these processes diverge into two distinct pathways tailored for specific applications: one for producing agricultural-grade pellets (Process 6) and the other for food packaging pellets (Process 7).

As shown in Table 17, Case Study 7 is characterised by extrusion, compatibilisation, and transformation operations applied to recycled polyethylene streams. The transformation stage incorporates additional materials, including ethylene-vinyl alcohol (EVOH), PA, compatibilizer, and Al, to produce the final pellets. The overall energy demand is largely

driven by extrusion-based operations, reflecting the high-power requirements associated with polymer melting, mixing, and shaping.

Table 17. Mass–energy balances of Process 6 (Case Study 7). Recyclable conventional pellet for agricultural applications.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Multilayer treatment	LDPE multilayers—875 kg	Vacuum reactor—360 kW	37 min	222 kWh	Bags waste plastics—520.6 kg	-	0.25 kWh/kg
Extrusion + compatibilisation	Bags waste plastics—520.6 kg	380 kW	1 h	380 kWh	Recycling plastic—500 kg Filter chunk—31 kg	-	0.46 kWh/kg
Transformation	LDPE—680 kg EVOH—80 kg PA—180 kg Compatibilizer—40 kg Al—20 kg	Extruder—4.7 kW Feeding—0.24 kW Cutting—1.05 kW Heater—1 kW	1 h	5.3 kWh	Pellets—1000 kg	None	0.0101 kWh/kg

Regarding Process 7 for producing food-packaging-grade pellets, the highest energy expenditure in this case derives from the thermal consumption required for vacuum decontamination of the pellets to enable their application in food-contact packaging. The KPIs for this process are itemised in Table 18.

Table 18. Mass–energy balances of Process 7 (Case Study 7). Recyclable conventional pellet for food packaging.

	Raw Materials Input	Rated Power	Time of Operation	Energy Consumption	Outputs	Waste	KPI
Multilayer treatment	LDPE multilayers	Vacuum reactor—360 kW	37 min	222 kWh	Bags waste plastics—520.6 kg	-	0.25 kWh/kg
Extrusion + compatibilisation	Bags waste plastics—520.6 kg	375 kW	0.75 h	281.3 kWh	Recycling plastic—500 kg Filter chunk—31 kg	-	0.34 kWh/kg
Transformation	Alfaten 2000 and Filter chunk 800 kg	Vacuum, cooling system 97.6 kW	8 h	780 kWh	Pellets—1000 kg	None	0.98 kWh/kg

3.5. Projected Energy Consumption Indicators After Process Scale-Up

This section presents the projected energy consumption indicators (kWh/kg) for each Case Study. The corresponding schematics (Figures 14–21) illustrate the integrated process configuration and the main mass flow streams, using the same box colour convention defined in Section 3.2 (blue-filled boxes for individual processing stages, and green-outlined boxes for recovered products). In addition, the reported specific energy consumption values are shown in two text colours: purple indicates the KPI obtained at the experimentally tested scale (Section 3.4), whereas green indicates the corresponding KPI projected to industrial scale (Section 3.5), to facilitate direct comparison between experimental and projected process performance. For each process, the notation "↑ kg ≡ [↓ arrows] kWh" summarises the scale-up effect, where the upward arrow denotes the increase in processing scale and the

number of downward arrows qualitatively indicates the relative magnitude of the resulting reduction in specific energy consumption, with the approximate numerical value given in parentheses. Thick vertical bars placed between processes indicate a boundary between processes tested at different, non-integrated scales.

3.5.1. Case Study 1—Processes 3, 4 and 5

A reference industrial capacity of 1000 kg/h of incoming multilayer waste is considered for the scale-up scenario. Based on the experimentally observed mass yields, approximately 800 kg/h of clean plastic fragments are obtained after pre-treatment and optical sorting, while 600 kg/h of PET/PE-rich fractions are forwarded to the final conversion stage.

Figure 14 shows a clear reduction in the specific energy consumption of mechanical and separation-based operations (Processes 3 and 4) when moving from pilot to industrial scale. This behaviour is primarily explained by classical scale-up effects, including (i) improved equipment utilisation, (ii) reduced relative contribution of fixed and idle loads, (iii) lower heat losses due to reduced surface-to-volume ratios, and (iv) improved energy integration under continuous steady-state operation.

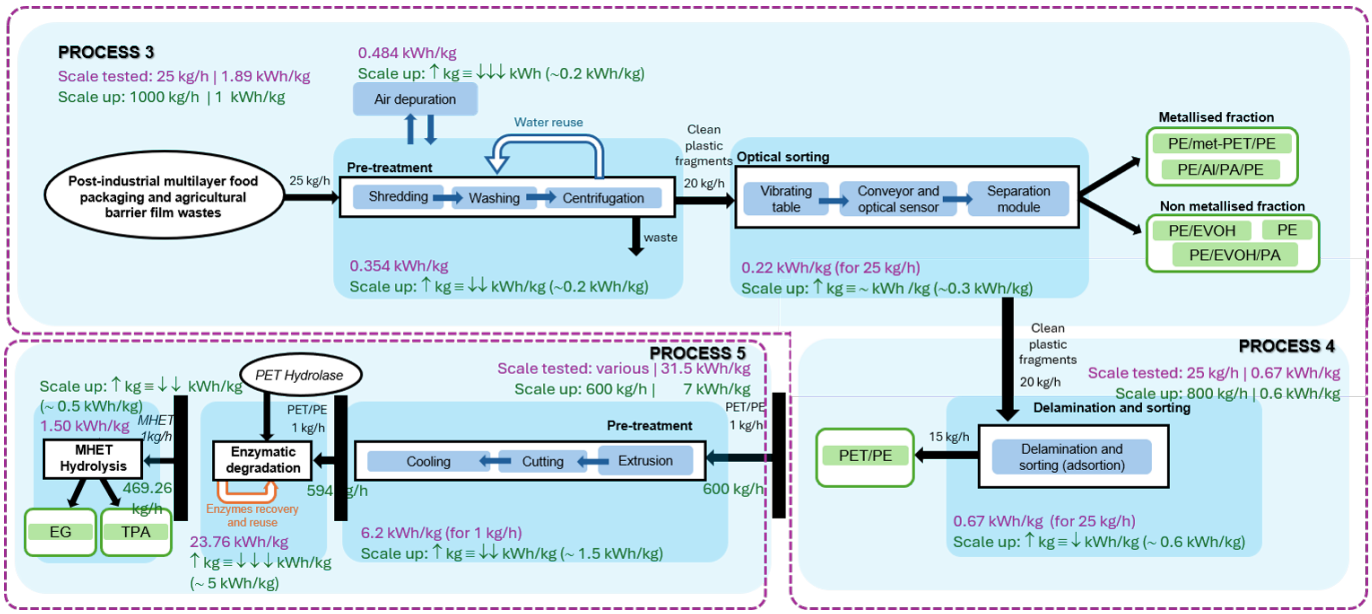


Figure 14. Case Study 1. Projected energy consumption for 1000 kg scale.

Process 5 exhibits fundamentally different scaling behaviour. Although extrusion-based conditioning benefits from standard scale-up effects similar to those observed in Process 3 and 4, the enzymatic degradation step does not scale according to equipment size alone. The high laboratory-specific energy consumption observed (up to 31.5 kWh/kg) is not representative of intrinsic process inefficiency, but rather a direct consequence of low throughput conditions, batch operation, extended residence times (48 h), and low solids loading. Under these conditions, fixed energy demands associated with agitation, temperature control, and auxiliary systems are normalised over a very limited mass flow, leading to artificially inflated specific energy indicators.

It is therefore important to distinguish between true scale-up effects and process intensification effects. While mechanical operations scale favourably, the reduction in energy intensity of the enzymatic step is primarily driven by changes in process configuration rather than by scale itself. These include increased solids loading, transition to continuous or semi-continuous operation, improved reactor design, enhanced mixing and mass transfer, and potential enzyme reuse or immobilisation strategies.

Even under optimistic industrial assumptions, enzymatic depolymerisation remains the dominant contributor to the overall energy balance. However, its apparent energy demand is expected to decrease significantly when moving from laboratory to industrial operation, not because of a change in intrinsic enzymatic kinetics but due to higher volumetric productivity and reduced impact of fixed energy loads.

Process 5 therefore represents a hybrid thermo-mechanical and biochemical pathway composed of extrusion-based pre-treatment, enzymatic PET depolymerisation, and MHET hydrolysis. Among these steps, enzymatic degradation constitutes the main bottleneck in both kinetic and energy terms, whereas MHET conversion and mechanical conditioning scale more efficiently and benefit more directly from process integration and intensification strategies.

Overall, the results highlight that the observed energy reductions with scale-up are governed by two distinct mechanisms: (i) classical engineering scale effects in mechanical and separation processes, and (ii) process intensification and change of operating regime in biochemical conversion steps. This distinction is critical for the correct interpretation of the energy KPIs and for the realistic assessment of industrial feasibility.

3.5.2. Case Study 2—Process 8

The Process 8 scheme comprises three parallel fermentation-based pathways, each yielding distinct value-added products from different substreams generated in Case Study 1 (EG and TPA) and Case Study 3 (lemon extract). Since only 180 L of EG and 300 L of TPA are obtained from Case Study 1, the scale-up of this specific process was not carried out at an industrial scale but rather at a semi-industrial scale as a valorisation route. Figure 15 shows both laboratory-scale KPIs (kWh/L) and projected semi-industrial scale KPIs for each unit, highlighting the effects of scale-up on specific energy consumption.

The fermentation process converting EG into glycolic acid and biomass was carried out at laboratory scale using a working volume of 3 L and a residence time of 7 days, resulting in a specific energy consumption of 17.7 kWh/L. This energy demand is mainly attributed to the continuous aeration required to maintain aerobic conditions and to the cooling necessary to control the exothermic reaction generated by microbial activity. When scaled up to a reference processing volume of 180 L, the KPI is expected to decrease to approximately 3 kWh/L due to the dilution of the fixed energy consumption associated with auxiliary equipment, improved thermal management, and continuous operation, while the biological reaction time remains the main limiting factor.

Biomass production from TPA, including both fermentation and freeze-drying stages, was performed at laboratory scale with a working volume of 1 L, yielding 4.3 g of PCA and exhibiting a high specific energy consumption of 62.7 kWh/L. This elevated value is primarily associated with the very small batch scale, which amplifies the contribution of auxiliary systems, together with the high energy demand of the freeze-drying process. Upon scale-up to an industrial processing volume of 300 L, the KPI is expected to decrease to approximately 15 kWh/L due to the improved energy efficiency achieved when processing larger volumes, particularly during freeze-drying and batch handling operations, as well as the potential for thermal integration and continuous operation.

The yeast fermentation process using lemon-derived substrates, followed by solvent evaporation to obtain microbial oil, was conducted at laboratory scale with 0.8 L of substrate. Specific energy consumptions of 43.9 kWh/L and 11.3 kWh/L were obtained for the fermentation and evaporation stages, respectively. These values are mainly associated with aeration requirements, temperature control, and solvent removal, whose impact is magnified under small-scale batch operation. When scaled up to a processing volume of 180 L, the KPIs are expected to decrease to approximately 2.5 kWh/L for fermentation and

0.5 kWh/L for evaporation. This reduction is attributed to the more efficient distribution of fixed energy demands, improved thermal integration, and the possibility of continuous operation of both the fermenter and the solvent recovery system.

Overall, the reduction in KPIs during scale-up is mainly driven by the dilution of the fixed energy consumption of auxiliary equipment over larger processing volumes, improved thermal management, and continuous operation. However, intrinsic biological constraints, such as microbial kinetics and the time required for product formation, limit the extent to which specific energy consumption can be reduced.

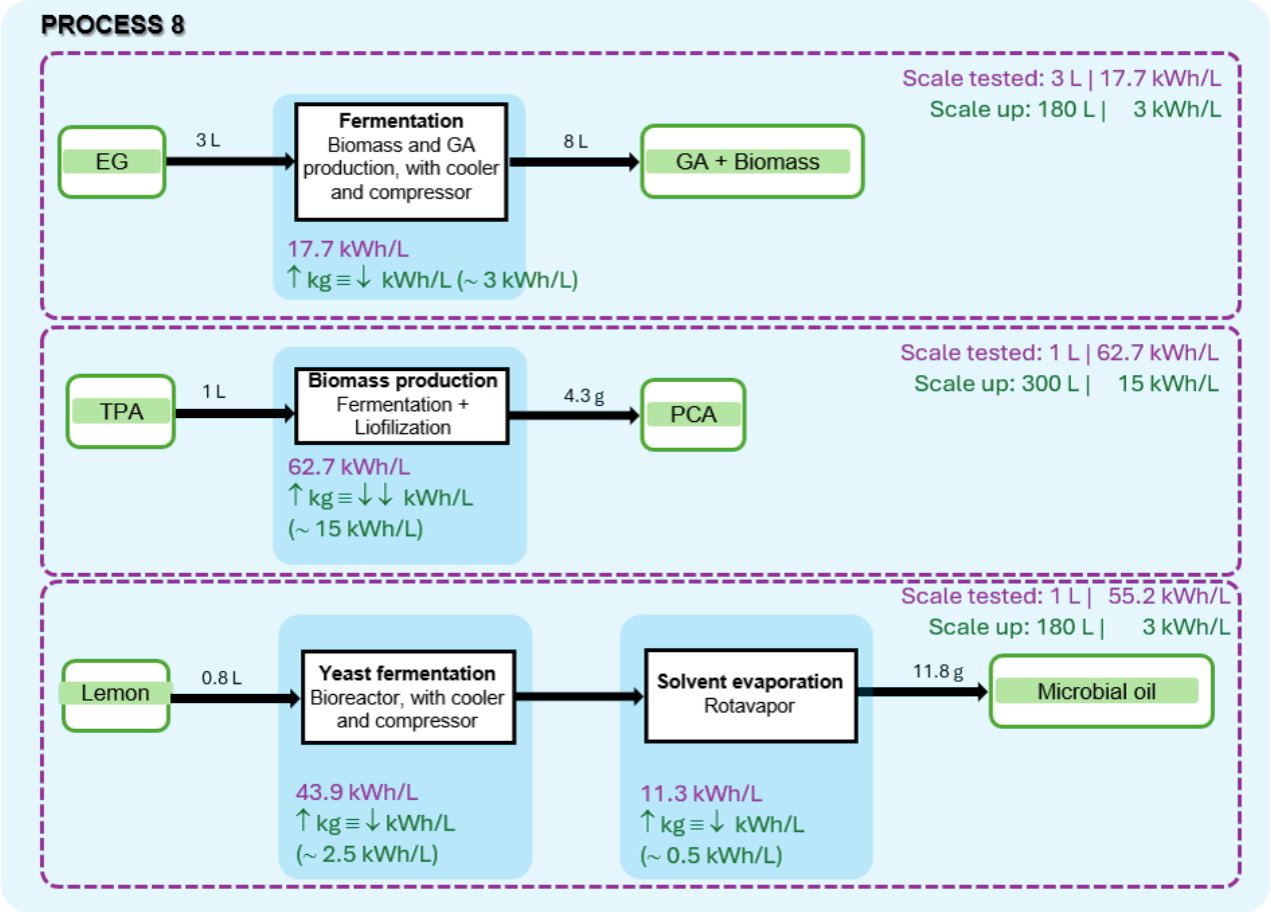


Figure 15. Case Study 2. Projected energy consumption for 180 L scale.

3.5.3. Case Study 3—Processes 1 and 2a

For the projection of the KPIs in Case Study 3 (Figure 16), it was first necessary to analyse both the experimentally tested scale and the projected industrial scale. The trials carried out in this Case Study were performed in batch mode, with each stage having its own operating time, ranging from 20 min to 4 days. Therefore, it is not strictly appropriate to refer to a continuous material flow expressed in kg/h for the experimental configuration. To ensure optimal utilisation of the process equipment at industrial scale, the units must be sized so that their production capacity is aligned with the raw material input rate. In this case, an inlet flow rate of 1000 kg/h of agrifood waste was selected, compared with the 150 kg/h capacity of the pre-treatment cutting unit and the 10 kg/h processed by the tested decanter. Considering this feed rate entering Process 1, and applying the same yield observed experimentally, approximately 800 kg/h would be directed to Process 2a.

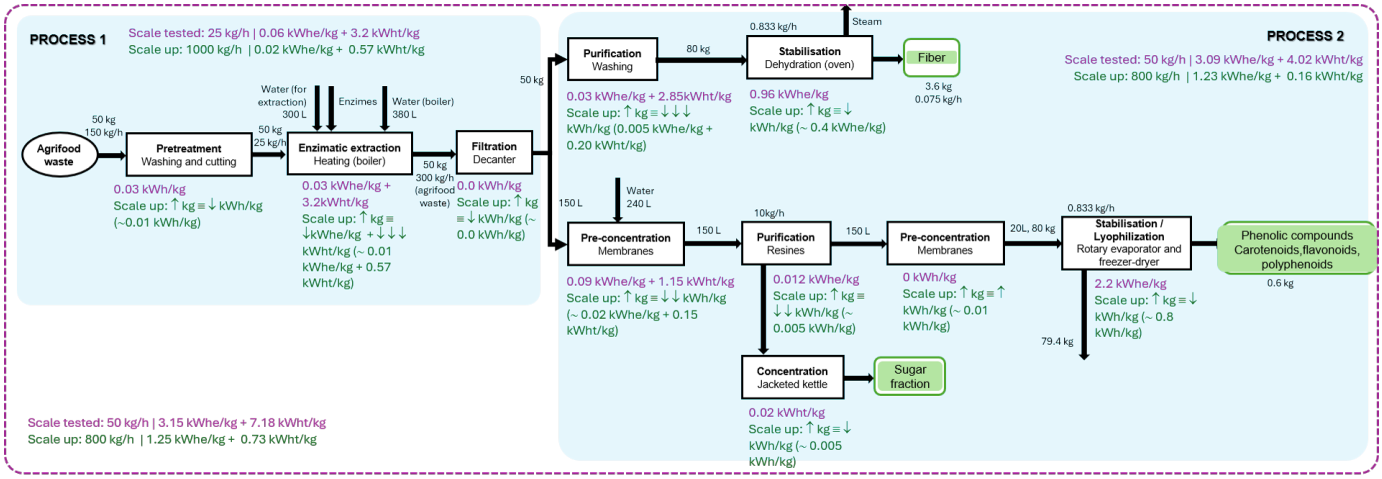


Figure 16. Case Study 3. Projected energy consumption for 1000 kg/h scale.

In Process 1, the washing and cutting pre-treatment step was scaled from 150 kg/h to 1000 kg/h and the consumption is expected to decrease from 0.02 kWh/kg to approximately 0.01 kWh/kg. This reduction is attributed to improved equipment utilisation at industrial scale, continuous operation and the dilution of auxiliary loads over a higher throughput.

The enzymatic extraction step was treated differently, as it requires heating of the reaction medium. At laboratory scale, this stage showed a thermal KPI of 1.6 kWht/kg, which is strongly affected by small batch operation, high relative heat losses and inefficient boiler utilisation. It also should be noted that the laboratory experiments were conducted on an open bench setup with significant thermal losses. These losses accounted for a larger share of the energy consumption than the heat required for process heating itself. In the scaled-up configuration, the process would be carried out in a reactor, and the thermal energy demand would be estimated according to Equations (1) and (2):

$$Q_{th} = m \cdot C_p \cdot \Delta T + Q_{losses} \quad (1)$$

$$Q_{losses} = U \cdot A \cdot \Delta T_{reactor-env} \cdot t_{reaction} \quad (2)$$

where

- Q_{th} is the total thermal energy required by the process (kWh or J).
- m is the mass of the processed material (kg).
- C_p is the specific heat capacity of the material ($\frac{\text{kJ}}{\text{kg}} \cdot \text{K}$).
- ΔT is the temperature increase required by the process (K or °C).
- Q_{losses} is the thermal energy lost to the surroundings during operation (kWh or J).
- U is the overall heat transfer coefficient between the reactor and the environment ($\text{W/m}^2 \cdot \text{K}$).
- A is the heat transfer surface area of the reactor exposed to the environment (m^2).
- $\Delta T_{reactor-env}$ is the temperature difference between the reactor contents and the surrounding environment (K or °C).
- $t_{reaction}$ is the reaction or processing time (s or h).

Using the available process-specific thermal intensity of 10.8 kWh/m^3 for the agrifood waste, together with the specific heat capacity of water ($4.18\ \text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$) for 6000 L of process water, the total thermal requirement at industrial scale was estimated at approximately 564 kWh per batch, considering both the agrifood waste and the extraction water. This corresponds to around 0.56 kWh_{th}/kg of agrifood waste input. The heating demand associated with the jacket water was not included in the process mass balance, as the jacket circuit is considered a thermal utility rather than an additional process-water input. Considering the

dimensions of two 3500 L jacketed reactors, the heat losses during operation were estimated at approximately 4.3 kWh. Therefore, the overall thermal KPI of the enzymatic extraction step was estimated at 0.57 kWh_{th}/kg.

The electrical contribution of the enzymatic extraction step was also reduced from 0.02 to 0.01 kWh_e/kg, reflecting the lower relative contribution of pumps, agitation and control systems at industrial scale.

The decanter filtration step was revised as an electrically driven separation operation. The electrical KPI was reduced from 0.15 to approximately 0.08 kWh_e/kg, reflecting the higher efficiency of industrial decanters and the dilution of fixed loads, while keeping a conservative value because centrifugal separation still requires a significant mechanical power input.

As a result, the overall energy KPI for Process 1 decreases from 0.19 kWh_e/kg + 1.6 kWh_{th}/kg at 35 kg/h to approximately 0.10 kWh_e/kg + 0.57 kWh_{th}/kg at 1000 kg/h.

In Process 2, the washing purification step was projected from 0.01 kWh_e/kg + 1.42 kWh_{th}/kg to approximately 0.005 kWh_e/kg + 0.20 kWh_{th}/kg. The electrical reduction is associated with more efficient pumping and continuous washing operation, while the thermal reduction reflects improved heat recovery, better insulation and the use of larger volumes. Nevertheless, a residual thermal demand was maintained because washing may require hot water or steam-assisted conditioning.

The dehydration oven was scaled from 0.51 kWh/kg to approximately 0.40 kWh/kg. In this case, the reduction is more moderate because dehydration is intrinsically energy-intensive and governed by moisture removal rather than only by equipment size. Industrial operation improves energy efficiency through better loading, insulation and potential heat recovery, but the drying duty remains a relevant contributor to the overall energy demand.

For the membrane pre-concentration step, the electrical KPI was reduced from 0.05 to 0.02 kWh_e/kg due to improved pump efficiency and operation closer to the optimal design point. However, the thermal KPI was not completely removed. Although membrane separation is mainly pressure-driven, the laboratory trials included heating to reduce viscosity and improve membrane performance. Therefore, at industrial scale, this thermal requirement was reduced from 0.57 to 0.15 kWh_{th}/kg, assuming thermal integration with the upstream enzymatic extraction step and insulated transfer of the already heated stream. Under this configuration, heat is not used as the separation driving force, but as feed conditioning and heat-loss compensation.

The resin purification, second pre-concentration and permeation stages were considered predominantly electrical operations. Their scaled KPIs were set at approximately 0.005–0.01 kWh/kg, corresponding to pumping, recirculation and pressure requirements. No thermal demand was assigned to these stages, unless future process data indicate that hot regeneration, thermal conditioning or heated cleaning-in-place is required.

The stabilisation/lyophilisation stage remains one of the most energy-intensive operations in Process 2. Its KPI was reduced from 1.3 to approximately 0.8 kWh/kg, reflecting the improved efficiency of industrial freeze-drying or evaporation systems, higher batch loading and better thermal integration. However, the reduction was kept moderate because phase-change operations impose a minimum energy requirement associated with water removal and product stabilisation.

Finally, the concentration step in the jacketed kettle was reduced from 0.01 to approximately 0.005 kWh_{th}/kg, as larger industrial equipment allows better insulation and lower relative heat losses. This value should be interpreted as valid for mild concentration duties. If substantial water evaporation is required, the thermal KPI should be recalculated from the latent heat of evaporation.

Overall, the scale-up projections are based on two complementary effects: the dilution of fixed electrical loads in mechanical and hydraulic operations, and the reduction of relative thermal losses in heated operations. Thermal energy was only retained where heating, dehydration, viscosity conditioning or product stabilisation is technically justified. This approach provides a more realistic representation of the expected industrial energy performance and avoids overestimating heat demand in unit operations that are fundamentally driven by mechanical, hydraulic or pressure-based separation mechanisms.

3.5.4. Case Study 4—Processes 1 and 2b

Case Study 4 describes an alternative valorisation route for the same agrifood waste stream, combining enzymatic extraction, fibre recovery and antioxidant extraction. Figure 17 schematically presents the experimental results and the projected KPI values under the scale-up scenario.

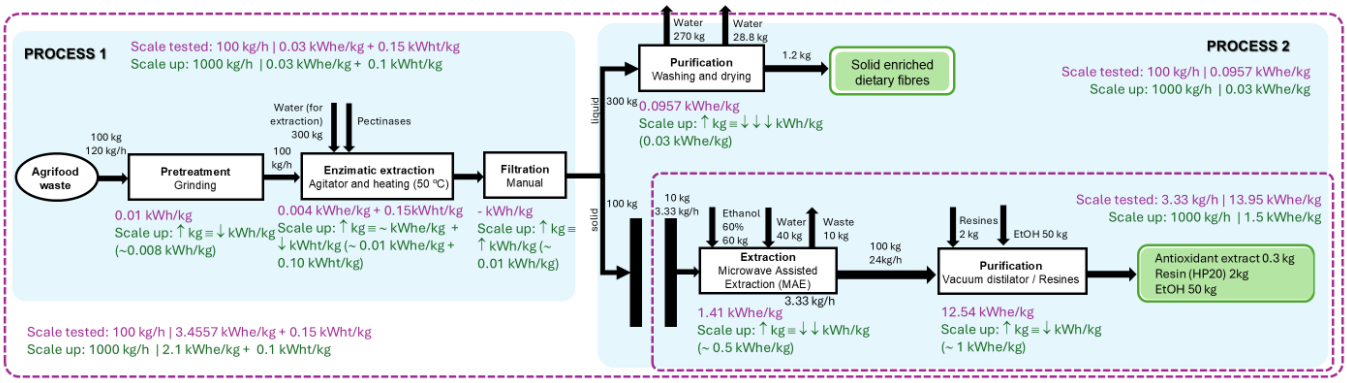


Figure 17. Case Study 4. Projected energy consumption for 1000 kg/h scale.

For Process 1, the tested scale was 100 kg/h, while an industrial reference capacity of 1000 kg/h was selected. The electrical KPI is projected to remain close to 0.03 kWh_e/kg. Although grinding and enzymatic extraction benefit from improved equipment utilisation at a larger scale, the transition from manual filtration to an industrial filtration system introduces an additional electrical contribution associated with pumping or mechanical separation. Therefore, the overall electrical KPI decreases moderately. The thermal KPI is expected to be reduced from 0.15 to approximately 0.10 kWht/kg due to lower relative heat losses, improved insulation and continuous operation, while still maintaining a thermal contribution because the enzymatic extraction requires heating of the aqueous medium to 50 °C.

The upper branch of Process 2b corresponds to the purification, washing, and drying of the liquid fraction to obtain solid enriched dietary fibres. The tested scale was 100 kg/h, as in Process 1, but due to water addition the inlet flow rate is 300 kg/h, corresponding with the natural output from process 1, maintaining the same factor of scale-up as Process 1. The electrical KPI is expected to be reduced from 0.096 to approximately 0.03 kWh_e/kg due to improved pumping, washing and handling efficiency at industrial scale.

The lower branch of Process 2b focuses on the recovery of antioxidant compounds from the solid fraction. This line was tested at a smaller scale, 3.33 kg/h, and was therefore treated separately from the fibre recovery route. For the industrial scenario, a capacity of 1000 kg/h was considered. This larger scale-up factor justifies a more significant reduction in specific energy consumption. The global electrical KPI was projected to decrease from 13.95 to approximately 1.5 kWh_e/kg, mainly due to improved utilisation of microwave-assisted extraction equipment, pumps, vacuum systems and resin columns.

Within the antioxidant recovery line, microwave-assisted extraction remains an electrically driven operation. The laboratory value of 1.41 kWh_e/kg is expected to decrease to approximately 0.50 kWh_e/kg at industrial scale due to continuous operation, higher filling factors and improved microwave energy utilisation. The subsequent purification step, based on vacuum distillation and resins, shows a very high laboratory KPI due to the inefficiency of small-scale solvent recovery equipment. At industrial scale, this step should be redesigned as an integrated solvent recovery and resin purification system. Under these conditions, the projected KPI is expected to decrease to approximately 1 kWh/kg, with the main contribution associated with ethanol-water solvent recovery rather than resin purification itself.

3.5.5. Case Study 5—Process 9

Figure 18 summarises the experimental energy KPIs obtained for Process 9 and the corresponding projections under the industrial scale-up scenario. The process converts liquid residues from Case Studies 2, 3 and 4 into dry microbial biomass through fermentation, tangential filtration and drying, followed by two downstream valorisation routes: PHBV extraction and carotenoid extraction.

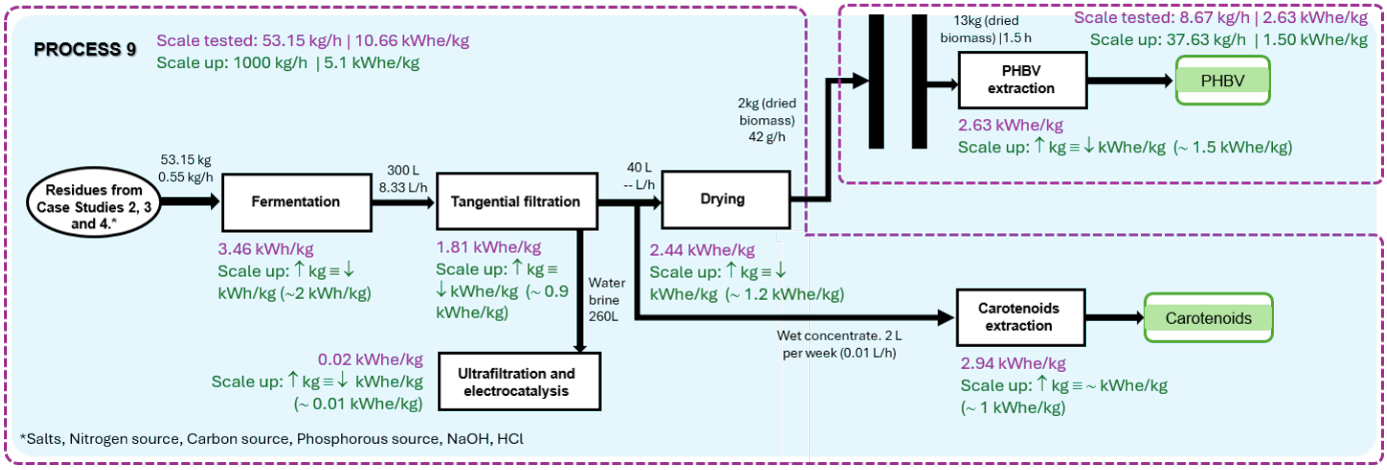


Figure 18. Case Study 5. Projected energy consumption for 1000 kg/h scale.

For the industrial projection, an inlet capacity of 1000 kg/h of liquid residues was selected as a representative continuous operating scenario. Based on the experimentally observed yield, 53.15 kg of liquid residue produced approximately 2 kg of dry biomass, corresponding to a dry biomass yield of about 3.76%. Therefore, the industrial configuration would generate approximately 37.63 kg/h of dry biomass, which is used as the reference flow for the PHBV and carotenoid extraction routes.

The overall KPI of Process 9 is projected to decrease from 10.66 to approximately 5.1 kWh_e/kg. This reduction is mainly attributed to continuous operation, improved equipment utilisation and dilution of fixed electrical loads. The fermentation stage is projected to decrease from 3.46 to approximately 2.0 kWh_e/kg. This reduction is moderate because fermentation remains constrained by biological kinetics, aeration, agitation and temperature control requirements.

Tangential filtration is projected to decrease from 1.81 to approximately 0.9 kWh_e/kg. This reduction reflects the use of larger membrane areas, improved pump efficiency, optimised recirculation loops and operation closer to the design point of industrial filtration systems.

The drying stage is projected to decrease from 2.44 to approximately 1.2 kWh_e/kg due to improved loading, better heat management and reduced relative losses at larger scale.

Nevertheless, drying remains an energy-relevant operation because water removal imposes an intrinsic energy demand. The ultrafiltration and electrocatalysis stage is projected to decrease only slightly, from 0.02 to approximately 0.01 kWh_e/kg, as its contribution is already very low.

The carotenoid extraction route remains more energy intensive. The laboratory KPI of 2.94 kWh_e/kg is associated with very small-scale batch operation and long processing time. At industrial scale, this KPI is projected to decrease to approximately 1 kWh_e/kg.

For the PHBV route, the extraction step itself is projected to decrease from 8.67 to approximately 1.50 kWh_e/kg.

Overall, the main energy hotspot of the overall valorisation chain becomes the carotenoid extraction route, while PHBV extraction remains comparatively low in energy demand.

3.5.6. Case Study 6—Process 10

Figure 19 presents Process 10, which represents the conversion of PHBV obtained in the valorisation route from Case Study 5 into biodegradable products through extrusion-based processing. The process was experimentally tested at a throughput of 10 kg/h, resulting in a specific electrical energy consumption of 2.63 kWh_e/kg. This value reflects the relatively high energy demand of small-scale extrusion, where fixed electrical loads associated with heating zones, screw drives, cooling systems, air supply, winding and process control are distributed over a limited material flow.

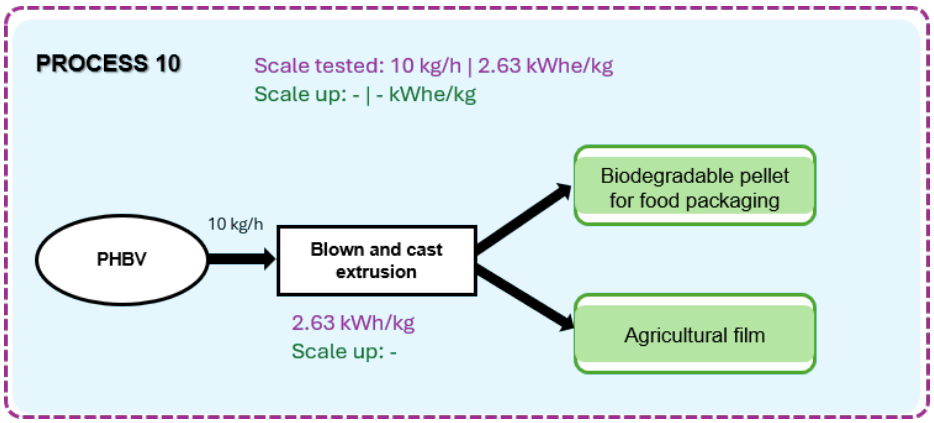


Figure 19. Case Study 6. No scale-up was considered.

As discussed in Section 3.5.8, the PHBV mass flow generated by Case Study 5 is significantly lower than any relevant industrial processing capacity for Process 10. Consequently, no industrial-scale projection is presented for this process, and the reported KPI corresponds to the experimentally tested scale (10 kg/h, 2.63 kWh_e/kg). Regardless of the operating scale eventually adopted, a buffer storage system for PHBV is required downstream of Case Study 5, with Case Study 6 operating in batch or campaign mode once a sufficient quantity of PHBV has accumulated, consistent with the integrated mass-flow framework described in Section 3.5.8.

3.5.7. Case Study 7—Processes 6 and 7

This Case Study considers two possible routes: one for the production of recycled pellets for agricultural applications (Route 1), and another for the production of pellets intended for food packaging applications (Route 2). In this Case Study, the tested scale corresponds to the capacity required to process the multilayer LDPE stream from Case Study 1, namely 1400 kg/h. However, a tested scale of 5 kg/h has been indicated, as this

corresponds to the capacity of the most restrictive subprocess, namely the transformation step of Route 1.

Based on the processing capacity of each subprocess, no scale-up was considered necessary for any stage except for the transformation step, which was scaled from a production capacity of 5 kg/h to 525 kg/h. It should also be noted that the decontamination stage of Process 6 has a lower capacity than required, namely 100 kg/h compared with the target capacity of 800 kg/h. In this case, the proposed solution is the implementation of eight identical parallel lines.

Regarding the calculation of the energy consumption KPI, the only unit operation that was not tested at the target scale was the transformation step of Route #1, which corresponds to the final stage of Process 6. Process 6 consists of the extrusion, cutting and heating of the pre-extruded LDPE; therefore, it can be considered a predominantly mechanical process with a minor heat contribution, since the electric heater accounts for only approximately 14% of the total installed power of this stage. Under scale-up conditions, friction-related losses are expected to decrease and the system is assumed to operate closer to its nominal design point, leading to a slight improvement in efficiency. Accordingly, a specific energy consumption KPI of 0.55 kWh/kg of input material was estimated for the scaled process at 1400 kg/h.

Figure 20 shows the parameters calculated for processes 6 and 7, grouped within the same Case Study as they share the first stage and differentiate in subsequent stages depending on the selected process route.

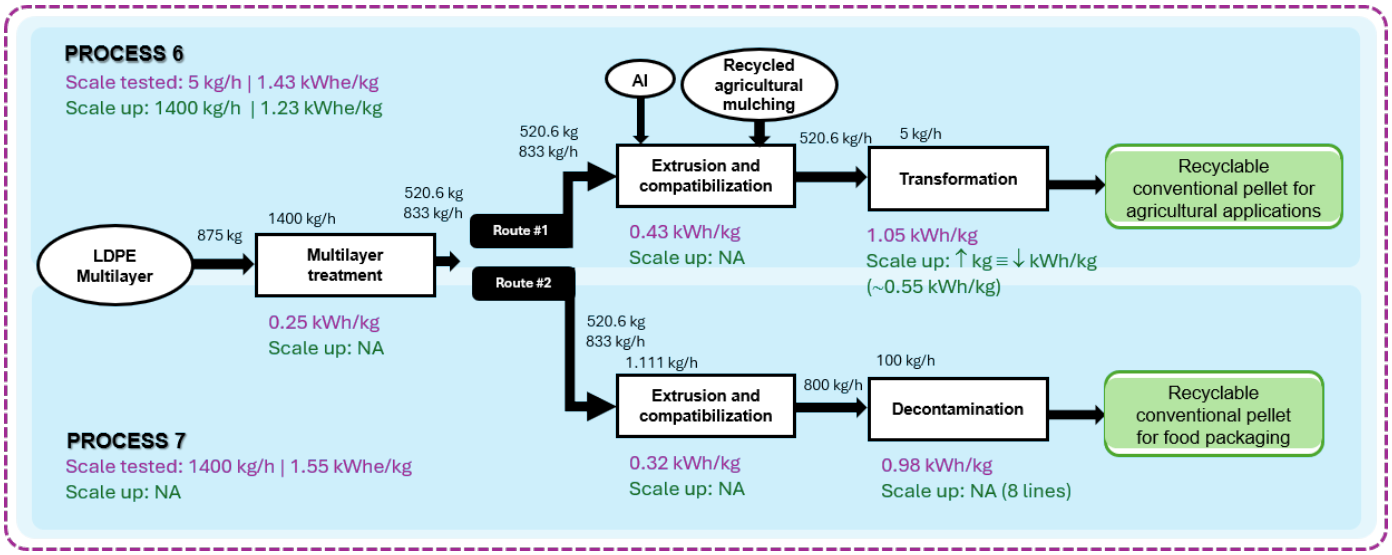


Figure 20. Case Study 7. Projected energy consumption for 1400 kg/h scale.

In short, virtually all KPIs are known through testing, except for that of the decontamination process, which could not be tested. As no empirical data are available, the consumption at the scale tested has been estimated based on formulation. Thus, a process consisting of vacuum decontamination has been considered, this being one of the methodologies included in Regulation (EU) 2022/1616 on recycled plastic materials and articles intended to come into contact with foods. The consumption of this process includes a thermal consumption component for pellet heating, thermal losses due to operation time, electrical consumption of the vacuum pump, and miscellaneous electrical consumption from auxiliary equipment such as ventilation, etc.

$$KPI_{vacuum} = \dot{Q}_{sensible} + \dot{Q}_{losses} + \dot{P}_{vac} + \dot{P}_{cooling} + \dot{P}_{aux} \quad (3)$$

The sensible heating has been calculated using Equation (4)

$$\dot{Q}_{sensible} = Q/m = C_p \cdot \Delta T \quad (4)$$

where C_p is the specific heat capacity of the polymer, in this case LDPE ($2.3 \frac{kJ}{kgK}$); ΔT is the temperature increment of the pellets, from inlet temperature to decontamination temperature (from 25 °C to 90 °C); and m is the mass flow rate of treated pellets. The calculated heat is $Q = 0.0415$ kWh/kg.

For the estimation of thermal losses, an overall heat transfer coefficient (U) of 1.5 W m^{-2} K^{-1} was assumed, considering the insulation characteristics of the reactor. The total heat transfer area (A) was estimated at 9 m^2, while the reactor and ambient temperatures were assumed to be 90 °C and 20 °C, respectively. A decontamination time of 8 h was considered. Based on these assumptions and using Equation (2), the thermal losses were estimated at 0.9 kWh_{th}/kg.

The electrical demand of the vacuum system was estimated from the average operating power of a standard vacuum pump divided by the treated pellet throughput. In a preliminary design stage, this contribution can be calculated using Equation (5).

$$\dot{P}_{vac} = P_{pump} \cdot LF \cdot t/\dot{m} \quad (5)$$

where P_{pump} is the nominal power of the pump, considered as 4 kW; LF is the average load factor of the pump, considered as 75%; and $\dot{m}$ is the LDPE pellet mass flow rate.

It should be noted that pellet heating in this stage is provided by an electric resistance heater, with a conversion efficiency of approximately 100%; the thermal energy supplied is therefore directly equivalent to the electrical energy consumed. Consequently, all energy contributions in this process—sensible heating, thermal losses, vacuum pump operation, and auxiliary cooling—originate from the same energy carrier (grid electricity) and are reported as a single specific electrical energy consumption (kWh/kg), in contrast to Case Studies 3 and 4, where thermal energy is supplied by a natural gas boiler and is therefore reported separately due to the different primary energy source and conversion efficiency.

For an industrial decontamination unit treating 800 kg/h during 8 h of recycled LDPE pellets, a vacuum pump power of 4 kW operating at partial load results in a specific electricity consumption of approximately 0.03 kWh/kg. This value is consistent with the moderate gas load expected during post-extrusion vacuum deodorisation, where the pump mainly removes residual air, desorbed Volatile Organic Compounds (VOCs) and minor leakage flows rather than continuously evacuating the full reactor volume.

On the other hand, the cooling contribution was estimated from the electrical demand of the condensation and cooling system divided by the treated pellet throughput. The cooling demand is mainly associated with auxiliary equipment such as cooling-water circulation, fans or a small chiller. For an industrial throughput of 800 kg/h, a cooling system power of approximately 3 kW was assumed, resulting in a specific contribution of around 0.004 kWh/kg. Finally, auxiliary equipment is considered negligible. The total KPI of the decontamination stage is calculated as 0.976 kWh/kg, corresponding mainly with heat losses.

3.5.8. Integrated Mass-Flow Analysis at Industrial Scale

Finally, the process scheme presented in Figure 13 was reproduced by integrating the flow rates considered in the scale-up analysis, resulting in Figure 21, where the scaled flow rates are represented in green.

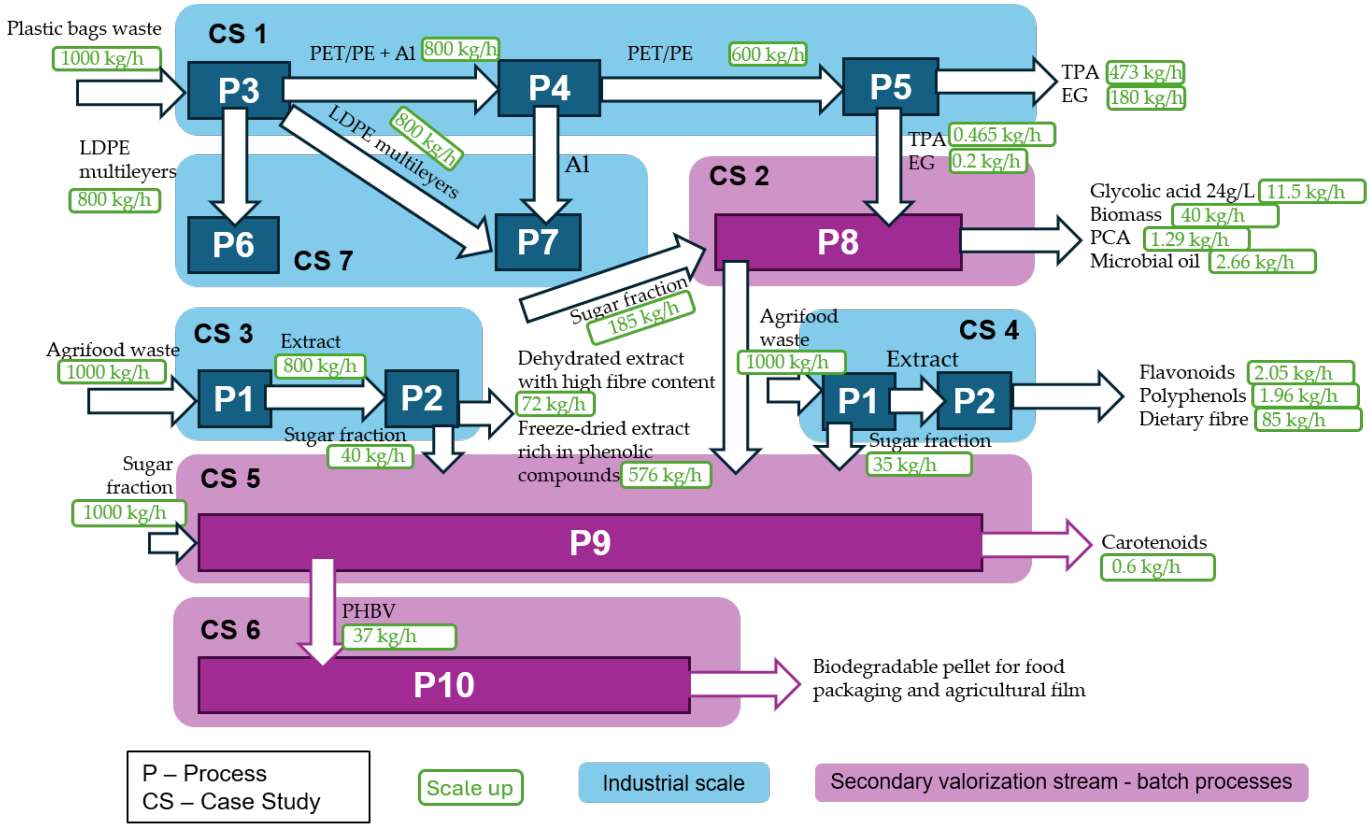


Figure 21. Integrated mass-flow framework for continuous industrial processing and batch valorisation of secondary streams.

Two situations were identified:

- On the one hand, CS5 requires a larger amount of sugar fraction than CS2, CS3 and CS4 can provide in order to achieve a reasonable carotenoid production rate.
- On the other hand, the PHBV flow produced in CS5 is insufficient to match the tested capacity of CS6; therefore, no scale-up was considered for this process.

Therefore, a key distinction was introduced between the representative processing capacity of each individual technology and the actual material flow available within the integrated case-study chain. While CS1, CS3-4 and CS7, represented in blue in Figure 21, define the main mass-processing routes and can be represented as continuous flows, the downstream valorisation steps, represented in purple in Figure 21, receive progressively smaller side-streams due to the cumulative effect of process yields. As a result, from CS2 and CS5-6, the available flow may be lower than the experimentally tested or industrially relevant capacity of the subsequent unit operations.

This situation was not treated as an inconsistency, but rather as an indication that the downstream processes should be operated in batch or campaign mode. In practice, the low-flow intermediate streams would be accumulated in buffer tanks or storage units and processed once a sufficient quantity is available. Therefore, the energy KPI of each unit operation was kept representative of its tested or projected operating capacity, while the integrated mass balance was calculated using the actual flow generated by the upstream processes.

Under this approach, the specific energy consumption of each process is not artificially penalised by assuming continuous operation far below its nominal capacity. Instead, the annual energy demand is obtained by multiplying the process KPI by the actual annual mass treated, while the operating time of each downstream unit is adjusted according to the available feedstock. This distinction is particularly relevant for high-value, low-throughput

valorisation routes, where process feasibility depends on campaign operation, intermediate storage or pooling of equivalent streams, rather than on direct continuous coupling with the upstream process.

3.6. Discussion of Results and Comparison with the Literature

To contextualise the energy performance reported in Section 3.4 (tested scale) and Section 3.5 (projected scale), the specific energy consumption obtained for each recovery process was compared with values reported in the literature for comparable technologies, including, where relevant, the conventional or virgin-feedstock production routes that the proposed valorisation pathways are intended to displace. It should be noted that literature values often correspond to different system boundaries, feedstock compositions, plant scales, and degrees of technological maturity than those of the prototypes tested in this work; the comparison is therefore indicative of the relative order of magnitude rather than a direct benchmarking exercise.

For the mechanical pre-treatment of multilayer plastic waste (Process 3, Case Study 1), the KPI obtained in this work (0.354 kWh/kg, plus 0.484 kWh/kg for the auxiliary air-depuration system, approximately 0.84 kWh/kg combined or 1.0480 kWh/kg referred to the 20 kg/h output) is of the same order of magnitude as the electricity consumption reported for mechanical recycling of LDPE into film products, approximately 1 kWh/kg of output for the entire process [56]. It should be noted that this reference does not disaggregate consumption by individual process stage (washing, shredding, extrusion), as the authors could not disclose plant-level detail due to a confidentiality agreement; the comparison should therefore be understood at the level of the overall pre-treatment stage rather than stage-by-stage. For reference, the cradle-to-gate production of virgin LDPE resin requires approximately 80.3 MJ/kg (22.3 kWh/kg) [57], two orders of magnitude above the total electrical demand of the mechanical recycling route analysed in this work.

For the enzymatic depolymerisation stage (Process 5), a directly comparable and rigorously documented benchmark is available from the techno-economic and life-cycle analysis of enzymatic PET recycling developed by the National Renewable Energy Laboratory (NREL) for a 150-metric-tons-per-day industrial-scale facility, which reports that enzymatically recycled TPA (rTPA) requires 69% less total supply-chain energy than virgin TPA (vTPA) production [58]. The KPI obtained in this work solely for the enzymatic degradation process (23.76 kWh/kg) is markedly higher than what this industrial-scale reference would imply, which is consistent with the fact that our data correspond to a very small, non-optimised batch reaction (1 kg PET, 48 h) rather than the continuously operated, 150 MTPD industrial facility modelled in that study, where fixed energy loads (heating, mixing, utilities) are distributed over a vastly larger throughput. Notably, even at this small, non-optimised laboratory scale, the KPI obtained for enzymatic degradation (14.25 kWh/kg, equivalent to 51.3 MJ/kg) already remains below the cradle-to-gate energy required to produce virgin PET resin (61.4 MJ/kg) [59], suggesting that the energy case for enzymatic PET recycling may hold even before industrial-scale optimisation is achieved.

For the biotransformation processes of Case Study 2 (Process 8), the specific energy consumption obtained (5.4–62.7 kWh/L inlet) is expected to be substantially higher than industrial fermentation benchmarks for microbial oil and organic-acid production, given the very small reaction volumes used in these laboratory trials (0.8–3 L) combined with multi-day reaction times. For context, conventional vegetable oil production requires approximately 0.8–1.2 kWh/kg oil depending on the extraction method (solvent extraction vs. traditional pressing) [60], equivalent to approximately 0.7–1.1 kWh/L when converted using a typical vegetable oil density of 0.92 kg/L. A direct comparison with the microbial oil produced in Case Study 2 is not possible on a strictly equivalent basis, since the KPI for

microbial oil in this work is expressed per litre of input rather than per kilogram of oil output. No verifiable literature benchmark for the manufacturing energy of glycolic acid or synthetic phenolic antioxidants (BHT/BHA) from petrochemical routes could be identified within the scope of this study; these remain acknowledged gaps for future comparative work.

For the extraction of bioactive/phenolic compounds from agri-food residues (Case Studies 3 and 4, Processes 1, 2a and 2b), the KPIs obtained (3.1521 kWh_e/kg + 7.1777 kWh_{th}/kg referred to the input in CS 3, or 262.68 kWh_e/kg + 598.14 kWh_{th}/kg on the basis of the 0.6 kg of final product obtained) substantially exceed the wide range reported for green extraction technologies applied to agri-food waste, which spans approximately 0.6–172 kWh/kg [61] of extracted product (100 t/year functional unit) depending on the extraction technology (e.g., microwave- or ultrasound-assisted vs. conventional solvent extraction). This difference is attributable to the very low final product yield obtained at this laboratory scale (0.6 kg of dehydrated liquid extract from an initial 50 kg batch of agri-food waste, i.e., approximately 1.2% mass yield), combined with the energy-intensive lyophilisation step required for its stabilisation, rather than to an inherent inefficiency of the extraction technology itself. It should also be noted that the literature reference corresponds to an industrial-scale facility (100 t/year), whereas the process analysed here has not yet been optimised or scaled beyond laboratory trials.

For Case Study 5, the specific energy consumption of the fermentation stage (3.53 kWh/kg) and of the downstream PHBV extraction and purification step (0.6346 kWh/kg) are markedly lower than the non-renewable energy demand reported for PHB production from lignocellulosic waste at laboratory scale (up to 5342 MJ/kg PHB, approximately 1484 kWh/kg, when pretreatment, delignification, enzymatic hydrolysis and fermentation stages are all included [62]). This difference is primarily attributable to the fact that the reference study accounts for the full lignocellulosic feedstock-conditioning chain, whereas Case Study 5 starts from an already available organic substrate and does not include equivalent feedstock-conditioning stages. For a more comparable reference, the total energy demand reported for PHA production from more conventional (non-lignocellulosic, non-waste-derived) routes ranges from 69.86 to 124.90 MJ/kg depending on the process scenario, with a broader literature median of 20–80 MJ/kg [63]. The combined energy demand of fermentation and PHBV extraction/purification obtained in this work (≈12.8 MJ/kg on a fermentation-plus-extraction basis, or ≈28.4 MJ/kg when filtration and drying are included) compares favourably with this range, suggesting that the waste-derived substrate used in Case Study 5 avoids some of the energy burden associated with feedstock conditioning in conventional PHA production routes. No directly comparable literature benchmark could be identified for the carotenoid-extraction stage; this is noted as a further gap for future comparative work.

Finally, for the extrusion- and compounding-based processes of Case Studies 6 and 7 (Processes 10, 6 and 7), the KPIs obtained (0.69–1.46 kWh/kg, or 3.3273 kWh/kg referred to the 500 kg/h of recyclable conventional pellet produced) are slightly higher than the specific energy consumption reported for laboratory-scale extrusion of polyolefins, which decreases from 0.931–1.282 kWh/kg for 1 h operation to 0.578–0.838 kWh/kg for 24 h operation as the fixed start-up energy is distributed over a larger processed mass [64]. This finding is particularly relevant to Case Studies 6 and 7, where the tested operations lasted between 37 min and 1 h, within the short-duration range where start-up energy is reported to account for 36–40% of total electricity consumption, compared with less than 3% for 24 h operation. For the aluminium fraction recovered and reprocessed in Case Study 7, the cradle-to-gate energy demand of primary aluminium ingot production is approximately 138.1 MJ/kg (approximately, 38.4 kWh/kg of primary energy) [65], consistent with the well-established

finding that aluminium recycling can save approximately 95% of the energy required for primary production.

Overall, three recurring causes explain the differences observed between the specific energy consumption reported in this work and the values available in the literature: (i) scale effects, since most of the analysed processes were tested on laboratory- or pilot-scale prototypes operating in batch mode, where fixed and auxiliary energy loads (including start-up energy) are not yet distributed over an industrially representative production volume or operating duration; (ii) differences in system boundaries, as several literature references report only a partial energy contribution or a simplified single-unit calculation, whereas the KPIs presented in this work integrate the total electrical demand of each prototype, including auxiliary and thermal management systems; and (iii) differences in technological maturity and feedstock-conditioning requirements, since several of the biochemical and enzymatic routes analysed in this work correspond to early-stage, non-optimised laboratory demonstrations, and in some cases start from a less feedstock-conditioning-intensive substrate than the reference studies. Notably, for two of the routes analysed (enzymatic PET depolymerisation in Case Study 1 and PHBV production in Case Study 5), the specific energy consumption obtained in this work already compares favourably with conventional or virgin-feedstock production benchmarks despite the small, non-optimised experimental scale, which is a promising indication for the prospects of these routes upon industrial scale-up.

Taken together, two of these comparisons provide a quantitative, rather than purely conceptual, basis for the resource-efficiency benefit attributed to the industrial symbiosis approach proposed in this work. By combining the specific energy consumption measured in this study with the virgin-material production benchmarks discussed above, the mechanical recycling route analysed in Case Study 1 is found to reduce specific energy consumption by approximately 96% relative to the cradle-to-gate production of virgin LDPE resin, while the enzymatic PET recycling route analysed in the same Case Study already performs below the cradle-to-gate energy of virgin PET resin even at non-optimised laboratory scale, a finding that is directionally consistent with the independent industrial-scale techno-economic analysis reporting a 69% supply-chain energy reduction for enzymatically recycled TPA. For the aluminium fraction recovered in Case Study 7, no case-study-specific energy value could be isolated for this minor stream component; it would nonetheless be expected to benefit from the substantial energy savings generally reported in the literature for aluminium recycling relative to primary production (approximately 95%). Overall, for the material streams for which a case-study-specific comparison could be established, these findings show that the recovery pathways integrated in this work already reduce resource requirements relative to running each process independently on virgin inputs, even before industrial-scale optimisation is achieved.

It should also be noted that the energy metrics discussed throughout this work are based on the specific electrical and thermal energy consumption of each process, expressed per unit of mass or volume processed. These metrics do not constitute a full life-cycle assessment, as they do not account for upstream impacts associated with raw-material extraction, transportation, or end-of-life stages, nor do they consider the origin or carbon intensity of the electricity supply used. Accordingly, references to the system being 'energy-efficient' throughout this paper should be understood specifically in terms of process-level specific energy consumption and not as a claim of overall environmental sustainability, which would require a comparative life-cycle assessment and an explicit characterisation of the energy source.

3.7. Limitations and Assumptions

Several limitations should be acknowledged when interpreting the results presented in this work.

First, each recovery process was evaluated in a single experimental run; consequently, no replicate-based variability or standard deviation could be reported, and the reproducibility of the measured mass and energy balances has not been statistically assessed.

Second, for a subset of prototypes operated at partner facilities where on-site monitoring by the authors' team was not feasible, energy consumption was estimated by combining partner-supplied measurements (total consumption or average power and operating time) with equipment technical/manufacturer data, rather than obtained from continuous on-site instrumentation; this estimation procedure introduces an additional source of uncertainty that has not been quantified. Furthermore, for some of the processes analysed in this work, complete mass flow data for all input and output streams were not available to the authors. This was particularly the case for certain formulations or auxiliary materials proprietary to the technology providers of the corresponding prototypes, for which the full compositional breakdown could not be disclosed. In these cases, the energy consumption and the resulting KPIs were calculated based on the mass flow rate or total throughput that could be verified, rather than on a fully closed mass balance for every stream. It is assumed that this incomplete disclosure of certain raw-material compositions does not affect the validity of the reported energy-based KPIs, since these are derived directly from the measured or estimated energy consumption and the processed material flow and not from the full compositional detail of the input streams.

Third, the industrial-scale KPIs presented in Section 3.5 are engineering-based projections derived from laboratory- and pilot-scale data combined with scale-up assumptions and, where applicable, first-principles calculations; they have not been validated through operation at industrial scale and should therefore be interpreted as estimates of expected performance rather than as directly measured values. Furthermore, the scale-up analysis presented in this work considers a single representative (base-case) scenario for each process, rather than a full set of conservative, base, and optimistic scenarios with an accompanying sensitivity analysis on key variables (e.g., solids loading, residence time, equipment load factor, heat recovery efficiency, fermentation productivity, and product yield). While such a multi-scenario analysis would provide a more complete characterisation of the achievable range of industrial performance, it was beyond the scope of the present work, which focuses on establishing a harmonised methodology for KPI calculation and a representative estimate of industrial-scale feasibility. A systematic multi-scenario sensitivity analysis is identified as a valuable direction for future work.

Furthermore, no inferential statistical methods (e.g., hypothesis testing, confidence intervals, or analysis of variance) were applied to the experimental data, since the single-replicate nature of the measurements described above does not provide an adequate basis for such analysis. Although the measurement instrumentation used has a manufacturer-specified accuracy of ±2.0% of reading (±0.13% additional resolution error; see Section 2.2), a formal propagation of this measurement uncertainty from the primary experimental variables (power, time, mass flow) to the process-level KPIs and to the industrially projected values presented in Section 3.5 was not performed. A quantitative uncertainty budget and its propagation through the mass–energy balances and scale-up calculations are considered beyond the scope of the present study and are identified as a valuable direction for future work.

Finally, several biochemical and thermal processes were tested under batch, small-scale, or low-throughput conditions with long residence times, which inflate their apparent specific energy consumption relative to continuous industrial operation; while the scale-up methodology (Section 2.4) explicitly accounts for this effect, the extent of the achievable reduction remains to be confirmed experimentally at a larger scale.

4. Conclusions

This work presented a methodology, combining direct experimental measurement, engineering-based estimation and industrial-scale projection, for identifying target products and designing, evaluating, and scaling up circular valorisation pathways for agri-food residues and multilayer plastic waste. It should be noted that only the laboratory- and pilot-scale results (Section 3.4) were directly measured or calculated from experimental data; industrial-scale performance (Section 3.5) was obtained through engineering-based estimation and projection and has not been validated through operation at industrial scale, as discussed in Section 3.7. By combining process definition, experimental mass and energy assessment, harmonised KPI calculation, and engineering-based industrial projection, the proposed framework provides a consistent basis for comparing heterogeneous recovery technologies and for supporting the design of integrated circular production systems.

The results show that energy performance depends strongly on the nature of the unit operation rather than on scale alone. Mechanical, physical-separation, and extrusion-based processes benefit consistently from classical engineering scale effects, with specific energy consumption typically falling below 1 kWh/kg once projected to industrial scale. In contrast, biochemical and thermally driven routes remain the dominant energy contributors even under industrial-scale conditions: enzymatic depolymerisation and fermentation-based processes, which reached up to 14–63 kWh per kg or litre of product at laboratory scale, are only partially mitigated by scale-up, since their apparent intensity stems mainly from batch operation and intrinsic biological or phase-change constraints rather than equipment size. Closing this remaining gap therefore requires process intensification rather than scale-up alone.

The integrated assessment further shows that circular valorisation platforms combining heterogeneous recovery pathways cannot be operated as fully continuous systems: the cumulative effect of process yields along the value chain requires downstream, high-value processes to operate in batch or campaign mode, supported by intermediate buffer storage. Rather than a limitation, this reflects how industrial symbiosis between agri-food and plastic-waste valorisation is technically realised in practice, coupling continuous upstream processing with flexible downstream operation.

Beyond the energy assessment itself, the results point to clear opportunities for further improvement, including enhanced heat integration and recovery, targeted process intensification, and operating strategies tailored to each recovery technology—particularly for biochemical and thermal routes. The integration of renewable energy sources and advanced energy management strategies also represents a promising direction for improving the environmental performance and operational flexibility of future industrial implementations.

Overall, although developed and demonstrated within the Agro2Circular project, the proposed methodology constitutes a transferable framework for the design, integration, and scale-up of future circular valorisation platforms involving multiple waste streams and complementary recovery technologies, supporting the transition towards more resource-efficient and sustainable production systems.

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Data Availability Statement: All data supporting the reported results are contained within the article. Specifically, the process-level data required to recalculate every experimentally determined KPI (nominal power, operating time, and mass and energy flow for each process) are provided in Tables 3–18 and in Table A1 (Appendix A), and the equations, engineering assumptions and unit conversion factors used to obtain the industrial-scale projected KPIs are described in the text of Section 3.5. Certain equipment and formulation details proprietary to the Agro2Circular technology-provider partners are not disclosed, in accordance with the confidentiality agreements already noted in Section 3.7 (Limitations).

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Conflicts of Interest: Authors Víctor Fabregat, Paloma González-Costa and Juana María Pagán were employed by the company Regenera Energy. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

E	Energy consumption
EG	Ethylene glycol
EVOH	Ethylene vinyl alcohol
FVH	Fruit, vegetables, and horticultural
GA	Glycolic acid
KPI	Key Performance Indicators
$KPI_{in,sub}$	KPI referred to the input of the subprocess
$KPI_{in,P}$	KPI referred to the input of the process
KPI_{P}	KPI of the process
KPIcs,in	KPI referred to input of the Case Study
LDPE	Low-density polyethylene
Min	Main Inlet mass flow rate/total mass processed
Mout	Product Mass flow
MHET	Mono(2-hydroxyethyl) terephthalate
PA	Polyamide
PCA	Protocatechuic acid
PE	Polyethylene
PET	Polyethylene terephthalate
PHBV	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)
t	Time of operation
TPA	Terephthalic acid
VOCs	Volatile Organic Compounds

Appendix A

Table A1. Summary of KPI of each process and case of study.

CS	P	Scale Tested	Subprocess	M_{out}	M_{in}	t	E	$KPI_{in,sub}$	$KPI_{in,P}$	KPI_P	$KPI_{cs,in}$
1	3	25 kg/h	Pre-treatment (process)	20 kg/h	25 kg/h	1 h	20.96 kWh_e	0.3544 kWh/kg	0.8384 kWh/kg	1.4144 kWh/kg	0.3544 kWh/kg
			Pre-treatment (air depuration)					0.4840 kWh/kg			0.4840 kWh/kg
			Separation	20 kg/h	20 kg/h	1 h	14.4 kWh_e	0.7200 kWh/kg	0.5760 kWh/kg		0.5760 kWh/kg
	4		Delamination	20 kg/h	20 kg/h	1 h	16.7 kWh_e	0.8335 kWh/kg	0.8335 kWh/kg	0.8335 kWh/kg	0.6668 kWh/kg
	5	1 kg/h	PET/PE pre-treatment	0.99 kg/h	1 kg/h	1 h	6.2 kWh_e	6.2000 kWh/kg	6.2000 kWh/kg	-	-
		1 kg/ 48 h	PET/PE enzymatic degradation to MHET	0.21 kg/h	1 kg	48 h	23.76 kWh_e	23.7600 kWh/kg	-		-
				0.78 kg/h							
		1 kg/3 h	MHET conversion	0.79 kg/h	1 kg	3 h	1.5 kWh_e	1.5000 kWh/kg	-		-
				0.30 kg/h							
2	8 (a)	3 L	Fermentation	8 L	3 L	7 days	53.1 kWh_e	17.7033 kWh/L	17.7033 kWh/L	17.7033 kWh/L	-
	8 (b)	1 L	Liofilization	4.3 g	1 L	5 days	62.7 kWh_e	62.7200 kWh/L	62.7200 kWh/L	62.7200 kWh/L	
	8 (c)	0.8 L	Yeast fermentation	0.9 L	0.8 L	3 days	35.1 kWh_e	43.9250 kWh/L	43.9250 kWh/L	55.1750 kWh/L	
			Solvent evaporation	11.8 g	0.9 L	8 h	9 kWh_e	10.0000 kWh/L	11.2500 kWh/L		
3	1	50 kg/h	Pretreatment		50 kg/h	1 h	1.7 kWh_e	0.0347 kWh/kg	0.0347 kWh/kg	0.0649 kWh_e/kg + 3.1620 kWh_{th}/kg	0.0649 kWh_e/kg + 3.1620 kWh_{th}/kg
			Enzimatic extraction		50 kg	107 min	1.4 kWh_e + 158.1 kWh_{th}	0.0280 kWh_e/kg + 3.1620 kWh_{th}/kg	0.0280 kWh_e/kg + 3.1620 kWh_{th}/kg		
			Filtration		50 kg	1 min	0 kWh_e	0.0002 kWh/kg	0.0002 kWh/kg		
	2 (solid)		Purification		50 kg	100 min	1.3 kWh_e + 142.3 kWh_{th}	0.0260 kWh_e/kg + 2.8460 kWh_{th}/kg	0.0260 kWh_e/kg + 2.8460 kWh_{th}/kg	0.7940 kWh_e/kg + 2.8460 kWh_{th}/kg	0.7940 kWh_e/kg + 2.8460 kWh_{th}/kg
			Stabilisation	3.6 kg/h	40 kg	48 h	38.4 kWh_e	0.9600 kWh/kg	0.7680 kWh/kg		
	2 (liquid)		Pre-concentration		150 L	30 min	4.7 kWh_e + 57.4 kWh_{th}	0.0313 kWh_e/L + 0.3827 kWh_{th}/L	0.0940 kWh_e/kg + 1.1480 kWh_{th}/kg	2.2932 kWh_e/kg + 1.1697 kWh_{th}/kg	2.2932 kWh_e/kg + 1.1697 kWh_{th}/kg
			Purification		150 L	180 min	0.6 kWh_e	0.0040 kWh/L	0.0120 kWh/kg		
			Concentration	0.016 m^3/h	Unspecified (permeate)	-	FALSO1.08 kWh_{th}	-	0.02166 kWh_{th}/kg		
			Pre-concentration		150 L	-	0 kWh	-	-		
			Stabilisation/ Lyophilization	0.6 kg/h	150 L	96 h	109.4 kWh_e	0.7291 kWh/L	2.1872 kWh/kg		
4	1	100 kg/h	Pretreatment		100 kg	0.8 h	1.1 kWh_e	0.0108 kWh/kg	0.0108 kWh/kg	0.0148 kWh_e/kg + 0.1500 kWh_{th}/kg	0.0148 kWh_e/kg + 0.1500 kWh_{th}/kg
			Enzimatic extraction		100 kg	1 h	0.4 kWh_e + 15 kWh_{th}	0.0040 kWh_e/kg + 0.1500 kWh_{th}/kg	0.0040 kWh_e/kg + 0.1500 kWh_{th}/kg		
			Filtration		100 kg	-	0 kWh	0.0000 kWh/kg	0.0000 kWh/kg		
	2 (liquid)		Ultrafiltration		300 kg	1 h	5.9 kWh_e	0.0197 kWh/kg	0.0197 kWh/kg	0.0197 kWh_e/kg + 0.0760 kWh_{th}/kg	0.059 kWh_e/kg + 0.2280 kWh_{th}/kg
			Dehydration	1.2 kg/h	30 kg	10–48 h	22.8 kWh_{th}	0.7600 kWh_{th}/kg	0.0760 kWh_{th}/kg		

Table A1. *Cont.*

CS	P	Scale Tested	Subprocess	M_{out}	M_{in}	t	E	$KPI_{in,sub}$	$KPI_{in,P}$	KPI_P	$KPI_{cs,in}$
4	2 (solid)	10 kg	Extraction (microwave)		10 kg	3 h	14.1 kWh_e	1.4100 kWh/kg	1.4100 kWh/kg	13.9500 kWh/kg	1.3950 kWh/kg
			Purification	0.5 kg, 2 kg and 50 kg	100 kg	100 h	125.4 kWh_e	1.2540 kWh/kg	12.5400 kWh/kg		
5	9	53.15 kg	Fermentation		53.15 kg	65 h	184 kWh_e	3.4609 kWh/kg	3.4609 kWh/kg	10.6573 kWh/kg	3.4609 kWh/kg
			Tangential filtration		300 L	24 h	96 kWh_e	0.3200 kWh/L	1.8062 kWh/kg		1.8062 kWh/kg
			Ultrafiltration and Electrodialysis		260 L	3 h	0.9 kWh_e	0.0035 kWh/L	0.0169 kWh/kg		0.0169 kWh/kg
			Drying		40 L	48 h	129.6 kWh_e	3.2400 kWh/L	2.4383 kWh/kg		2.4383 kWh/kg
			Carotenoids extraction	Unspecified	2 L	120 h	60 kWh_e	30.0000 kWh/L	1.1289 kWh/kg		1.1289 kWh/kg
						48 h	96 kWh_e	48.0000 kWh/L	1.8062 kWh/kg		1.8062 kWh/kg
		13.00 kg	PHBV extraction and purification	500 g	13 kg	1.5 h	8.3 kWh_e	0.6346 kWh/kg	0.6346 kWh/kg	0.6346 kWh/kg	0.6346 kWh/kg
6	10	13 kg/h	Compounding and compatibilization	9.7 kg/h	10 kg	0.75 h	26.3 kWh_e	2.6250 kWh/kg	2.6250 kWh/kg	2.6250 kWh/kg	2.6250 kWh/kg
7	6 and 7	1400 kg/h	Multilayer treatment	521 kg/h	875 kg	37 min	222 kWh_e	0.2537 kWh/kg	0.2537 kWh/kg	-	0.2537 kWh/kg
	6		Extrusion and compatibilization	500 kg/h	833 kg	1 h	380 kWh_e	0.4562 kWh/kg	0.4343 kWh/kg	0.6940 kWh/kg	0.4343 kWh/kg
			Transformation		520.6	1 h	5.3 kWh_e	0.0101 kWh/kg	0.0060 kWh/kg		0.0060 kWh/kg
	7		Extrusion and compatibilization	31 kg/h	833 kg	0.75 h	281.3 kWh_e	0.3376 kWh/kg	0.3214 kWh/kg	1.4671 kWh/kg	0.3214 kWh/kg
			Decontamination	500 kg/h	800 kg	8 h	780.4 kWh_e	0.9755 kWh/kg	0.8919 kWh/kg		0.8919 kWh/kg

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