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Systematic Review

Systematic Evidence Mapping to Assess the Sustainability of Bioplastics Derived from Food Waste: Do We Know Enough?

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Abstract: The production of bioplastics from food loss and waste (FLW), termed FLW-derived bioplastics, is considered an attractive alternative to first-generation bioplastics. To our knowledge, a clear understanding of the sustainability performance of FLW-derived bioplastics from environmental, economic, technical, and social aspects is still lacking. This systematic evidence mapping aims to fill this gap by undertaking a reality check on the life cycle sustainability performance of FLW-derived bioplastics from a multidimensional perspective underpinned by systems thinking approach to assess their potential to revolutionise the plastics economy. Results revealed that FLW-derived bioplastic production is highly complex and uncertain. The low technological readiness of FLW valorisation processes and the under-researched logistics of FLW management on a regional scale currently withhold advancement in this field. Nonetheless, progress is looming, and ensuring that FLW-derived bioplastics production enables the transition toward a sustainable bioeconomy is critical. Innovation in both the food and plastics value chains is urgently needed to address their challenges and mitigate pollution. Yet, any steps forward need to be holistically calculated to yield sustainability benefits and prevent unintended consequences.

Keywords: bioplastics; sustainability assessment; systematic evidence map; food supply chain; second-generation feedstock

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1. Introduction

Bioplastics have gained increased interest due to their ability to reduce dependence on fossil resources and claimed potential to reduce greenhouse gas (GHG) emissions [1]. Bioplastics include bio-based-biodegradable, bio-based-non-biodegradable, and petrochemical-based biodegradable plastics (for definitions, see [2,3]). They are increasingly being used in packaging (e.g., food wraps and films), electronics (e.g., keyboard elements and mobile casings), and in the automotive (e.g., seat and airbag covers), agriculture (e.g., mulching films), textile (e.g., hangers) and toy sectors. Bioplastic's most general application, at present, remains the shopping bag [2]. Wider adoption of bio-based plastics faces logistics challenges, such as technological maturity and costs associated with feedstock supply and production [4]. The additional demand for land to cultivate crops for feedstock, known as 1st-generation feedstock, puts extra pressure on land at the risk of jeopardising food security and negatively impacting biodiversity [2,4].

An alternative solution is the production of bio-based plastics from waste streams generated across the food value chain, known as a 2nd-generation feedstock. The EU Waste Framework Directive (2018/851) defines food waste as "*all food as defined in Article 2 of*

Regulation (EC) No 178/2002 of the European Parliament and of the Council (i.e., substance or product, whether processed, partially processed or unprocessed, intended to be or reasonably expected to be ingested by humans) that has become waste" [5]. Following the definitional framework of the Food and Agriculture Organization of the United Nations (FAO), the decrease in quantity (i.e., mass) or quality (i.e., nutritional value) of food caused by the production and distribution stages of the food supply chain due to natural disasters and inefficiencies related to infrastructure, logistics, knowledge and technological barriers is known as *food loss* [6,7]. Food that has been discarded (including inedible parts from food preparation), spoiled or expired caused to consumer shopping and eating habits, poor stock management or neglect is known as *food waste* [6,7]. Food residues/scraps generated by the retail sector, food service providers, and consumers are *food waste*, while food residues/scraps produced during processing are known as *food loss* [8].

Additionally, *food by-products* are residues from the food sector that are unwanted but have the potential to be recovered and valorised into value-added products (i.e., new products with market value) that can be introduced back to the system [9]. For example, food waste at the consumption stage constitutes a source of fatty acids, nutrients, proteins and starch [10]. Nearly 50% of whey, a valuable substrate for microbial growth with high content of fatty acids (i.e., acetic, butyric, and lactic), proteins and vitamins, is wasted [11]. In Europe, waste whey is a popular waste substrate that is processed into polylactic acid (PLA) and polyhydroxyalkanoates (PHAs)—two biopolymers that are commonly used for the production of bioplastics [10,12,13]. A notable example is a team of 21 partners from 10 European Union member states that launched a collaborative project called YPACK to scale up the use of cheese whey for producing PHA in packaging applications [14]. Here, *food loss* and *food waste* (incl. *food by-products*), referred to hereafter as FLW, are combined to denote the recovery of food residues across the entire food supply chain for the production of bioplastics.

To empower the use of FLW in the production of bioplastics, academics and practitioners should evaluate their sustainability [15]. Currently, studies focus on assessing the technical performance of bioplastics production [16]. They look into the composition and structure of food-based substrates [17], valorisation techniques [10], characterisation of bioplastics properties [18] and parameters and conditions that can affect the production yield [11,19,20]. Some studies have gone a step beyond to either complete preliminary environmental [21–23], economic [24,25] or techno-economic [26] assessment of bioplastics produced by specific food waste substrates, but not looking at all aspects in a holistic, integrated manner. To our knowledge, a clear understanding of the sustainability performance—one that can integrate environmental, economic, social and technical aspects—of bioplastics produced from 2nd generation feedstock, specifically food waste, is still lackingan. The present work seeks to fill this gap by conducting a reality check on the life cycle sustainability performance of FLW-derived bioplastics by amassing existing evidence and uncovering whether existing information supports FLW-derived bioplastics uptake as a viable and sustainable alternative to conventional plastics, as it is currently assumed. This analysis aims to interrogate the potential of this innovation to revolutionise the plastics economy by undertaking the following objectives:

(i) collect peer-review evidence on the sustainability performance of FLW-derived bioplastics from a multidimensional perspective including environmental, economic, social and technical aspects through systematic evidence mapping; and
(ii) critically assess whether the *status quo* of FLW-derived bioplastics from a sustainability perspective would enable their wider adoption based on this evidence mapping.

To address the objectives of this work, the following sections are provided: (i) background information on the sources of FLW-derived bioplastics as well as the main biorefinery processes for their production (Section 2); (ii) the methodological steps for the systematic evidence mapping (Section 3); mapping of the existing evidence on the sustainability performance of FLW-derived bioplastics based on the lifecycle stages and sustainability aspect

(Section 4); critical assessment of the *status quo* of FLW-derived bioplastics (Section 5); and concluding remarks (Section 6).

2. Background Information

FLW-derived bioplastics can be either plant or animal-based. Plant-based bioplastics originate from crop residues, fruit, vegetable and cooking oil waste (e.g., citrus peels, grapes from wine production, straw, rice and peanut husks, corn stover, and coffee grounds). Animal-based bioplastics may come from animal by-products (e.g., bones and skin), dairy residues (e.g., whey), and fish residues (e.g., prawn shells) [27,28]. Therefore, a diversity of carbon sources can be valorised for FLW-derived bioplastics production [10,29–31].

Figure 1 shows the possible source of FLW across the food value chain [10,32].

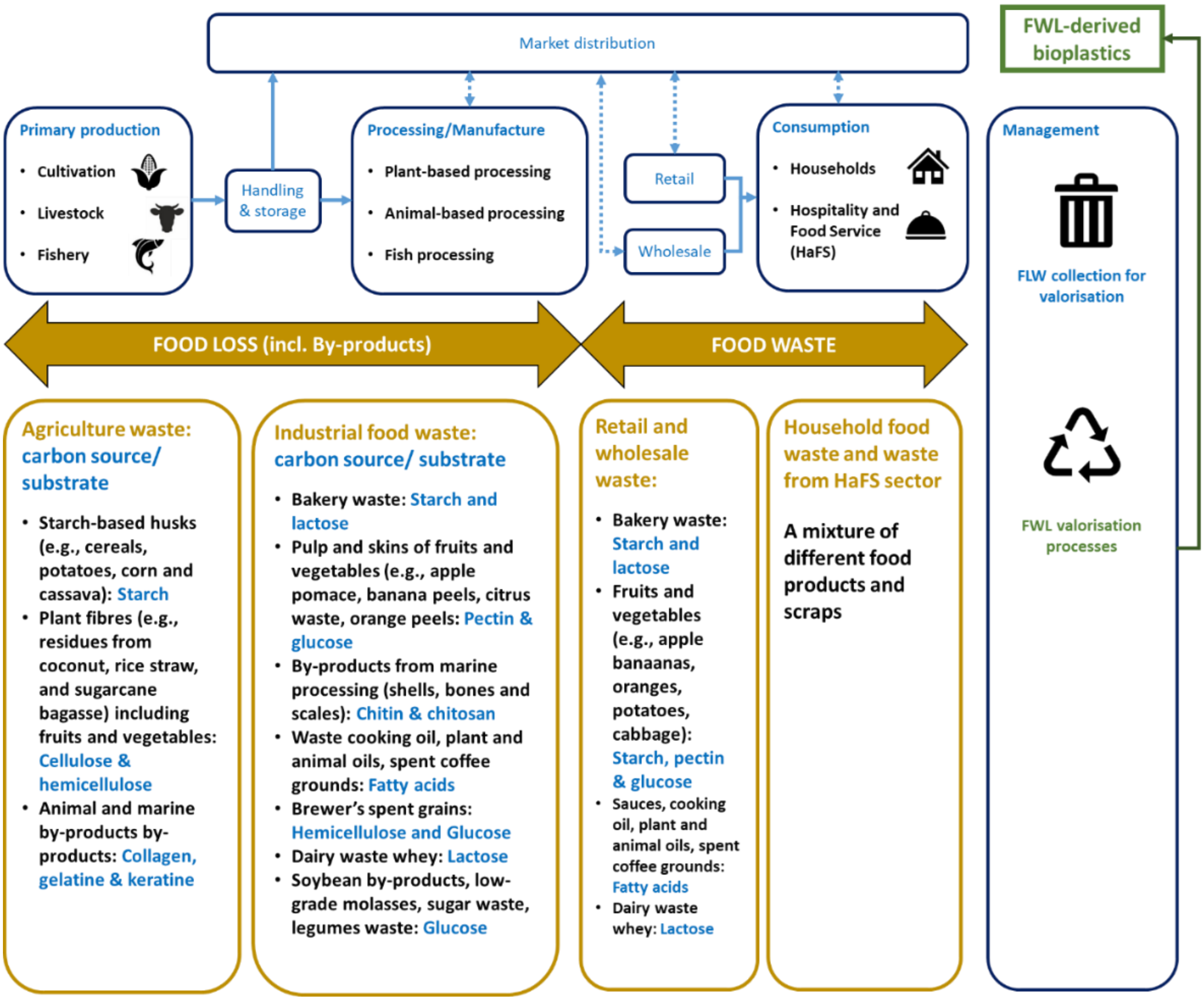


Figure 1. Generation of FLW across stages of the food value chain.

Biorefining processes can convert macronutrients (i.e., carbohydrates, proteins and lipids) contained in FLW into smaller chains molecules such as sugars, amino acids, and fatty acids, that can be recovered and used as a substrate for the production of bioplastics [33,34]. Biorefinery is defined as a framework or structure that employs a range of processes for converting biomass into a spectrum of energy (i.e., biofuels, power, heat) and value-added (i.e., chemicals, materials, food) products in a sustainable manner [35].

The main production methods employed in biorefinery facilities for the production of FLW-derived bioplastics include [31,36]:

1. Direct extraction of biopolymers from biomass (e.g., extraction of polysaccharides, such as starch and cellulose, and proteins, such as gluten);
2. Production by a range of microorganisms cultured under several nutrient and environment conditions conducted in batch and fed-batch reactors. Characteristically, PHAs are synthesised intracellularly by PHA-producing bacteria, such as *Cupriavidus necator*;
3. Synthesis from bio-based monomers through fermentation of carbohydrates by bacterial microorganisms into biopolymer precursors (i.e., renewable bio-based monomers) followed by polymerisation processes, such as PLA.

In the last two methods, extraction and purification follow biopolymer synthesis, known as downstream processing [34,37]. Downstream processing can be conducted chemically, mechanically and biologically. For example, solvent extraction, chemical or enzymatic digestion, and cell biomass disintegration are chemical processing methods [34]. Mechanical processing usually involves disruption with a bread mill or high-pressure homogenisation. Biologically, animals such as mealworms and rats are fed with dry bacterial cells containing PHAs. Lastly, biopolymers are processed through conventional mechanical techniques, such as extrusion, casting and moulding or a combination of them, affecting the final properties of FLW-derived bioplastics [31].

A range of pre-treatment methods for monomers' partial or total liberation from FLW and for increasing the accessibility of macronutrients by microorganisms are employed before the downstream processing [10]. These pre-treatment technologies can be grouped into:

- Physical (i.e., filtration, reverse osmosis, centrifugation, ultrasound, microwaving, milling, high-pressure homogenisation, electro-kinetic irradiation) [10];
- Thermal (i.e., pasteurisation [26], drying, thermal treatment at high temperature, freeze/thaw [16]);
- Chemical (i.e., coagulation, flocculation, acid treatment [11], alkali treatment and oxidation treatment [16]);
- Biological [10] (i.e., utilisation of white-rot fungi for delignification, enzymes assisted treatment, anaerobic treatment and aerobic treatment [16]); and
- Hybrid [16].

This Section shows that there is a wide variety of biorefinery processes for producing FLW-derived bioplastics, indicating different needs in terms of energy and raw materials. In turn, this can affect the multidimensional value of the end product. For example, a combination of centrifugation with anaerobic treatment as a pre-treatment process of olive oil mill effluents was reported to provide considerably higher production yields than untreated effluents [38]. Specifically, the production yield of volatile fatty acids (VFAs)—the substrate for PHA production—increased from 25% (i.e., 9.2 g chemical oxygen demand (COD)/L) to 36% (i.e., 13 g COD/L) [38]. Therefore, grouping the polymer production technologies would enable a better understanding of the sustainability of FLW-derived bioplastics.

3. Methodology

This systematic evidence map aims to establish the status quo of the FLW-derived bioplastics from a sustainability perspective using the complex value optimisation for resource recovery (CVORR) approach. CVORR framework constitutes an analytical approach for the study of resource recovery processes in the waste management field. In the CVORR approach factors such as the environmental, technical, economic, social and institutional aspects underlying resources and waste management need to be adequately understood for sufficiently meaningful conclusions to be drawn. CVORR's structure allows users sufficient flexibility to choose between a 'snap-shot' of the status quo and life cycle sustainability evaluation of resources and waste, and an extensive valuation and assessment of current and (potential) future conditions and interventions [39,40]. For the systematic evidence mapping the protocol development aimed to follow as far as practicable the recommendations for conducting systematic reviews in toxicology and environmental health research (COSTER) [41].

3.1. Eligibility Criteria

We articulated our objective using a PO (Populations-Outcomes) statement, where the population (P) refers to FLW-derived bioplastics, and outcome (O) their sustainability performance from a multidimensional perspective environmental, economic, and technical. Eligibility criteria were applied to produce an accurate framework that addresses the aim of this work. These criteria, including the PO statement, are provided in Table 1.

Table 1. PO statement and eligibility criteria for the sustainability assessment of FLW-derived bioplastics.

PO Statement		**Inclusion Criteria**	**Exclusion Criteria**
Population	Bio-based plastics from waste generated across the food value chain	FLW from all stages of the supply chain (e.g., agriculture, processing, household, wholesale and retail, catering) used for bioplastic production; Any type of bio-based plastic produced by FLW.	Bioplastics obtained from primary feedstock (i.e., non-edible crops); Bioplastics from any other non-food secondary and third-generation feedstock (e.g., algae); Unspecified source of feedstock origin; Bio-based plastics that used FLW as filler; Bioplastics produced from mixtures of waste streams (e.g., manure and FLW).
Outcome	Sustainability assessments (environmental, economic, technical, social) of FLW-derived bioplastics	Sustainability assessments at any FLW-derived bioplastics' lifecycle stage; Economic assessments at any FLW-derived bioplastics' lifecycle stage; No limitation to geographical origin; Studies conducted at any scale (lab, pilot, and industry) that provide insights into technical parameters and their effect on the properties and technological performance of FLW-derived bioplastics.	Perspectives, short communication and opinion letters; Studies focused on exploring the bio-chemical kinetics and processes of converting FLW into a substrate for bioplastics without providing evidence on the properties of bioplastics and production efficiency.

Grey literature was not included in this work, although it is not strictly excluded, to restrict our focus on well-established and high-quality evidence regarding sustainability assessments.

3.2. Search Strategy

For the search strategy, we created three lists of key terms. The two lists referring to population included all synonyms and types of secondary feedstock titled "Waste from food supply chain" (28 search terms) and synonyms and types of bio-based plastics from secondary feedstock titled "Second generation bioplastics" (10 search terms). The list referring to Outcome included "Sustainability assessment" related terms (10 search terms). These lists and the search terms are provided in *Supplementary Material A*. We then searched for peer-reviewed literature in three bibliographic databases, including Web of Science Advanced Search (WoS), Scopus, and ScienceDirect. We combined all individual keywords of each list with the OR Boolean operator resulting in three long search strings (one for each list), which in turn were connected with the AND Boolean operator. Since each database may apply different norms for advanced searching, we modified some search terms accordingly. For example, the proximity operator is defined as NEAR/n and W/n for

WoS and Scopus, respectively. Moreover, to capture keywords written differently in British or American spelling and singular and plural forms, we used the * symbol. All references were managed by the citation reference manager EndNote.

The process of the systematic evidence map was managed and coordinated with the support of the online tool CADIMA—a free web tool that facilitates the documentation and process steps of systematic reviews. At this step, we applied eligibility criteria to the retrieved reference list from databases based on the search strategy. Specifically, the stage of screening was carried out by three researchers. As part of an initial consistency check, team members screened 200 studies by reading titles and abstracts in parallel to detect potential discrepancies and clarify eligibility criteria if needed. The remaining preliminary screening (titles/abstracts) was conducted by one researcher, while the full-text screening of the remaining reference list was conducted by two researchers independently.

3.3. Data Collection Process

An excel template was designed according to the eligibility criteria and data provided by the included studies (The template is provided in *Supplementary Material B*). Specifically, the template includes meta-data (author, year), FLW type (e.g., household food waste, waste cooking oil, crop residues, etc.), food supply chain stage, primary carbon source from food waste used for bioplastic production, biopolymer type, sustainability perspective (i.e., environmental, economic, technical, and social), country (i.e., geographical origin of the food waste and bioplastic manufacturing). Where possible quantitative data were extracted and recorded from included studies mainly for environmental and economic assessment.

4. Results

Following the COSTER protocol and formulating the PO statement reported (Table 1), 61 eligible studies were selected and included in this research work. These eligible studies entail the research on assessing the sustainability of FLW-derived bioplastics. Review studies and studies that looked into the use of FLW as filler material in bioplastics, are out of the scope of this work, and were excluded from this evidence map.

Figure 2 presents the flow diagram detailing the results of the literature-searching strategy.

Most studies (36 out of 61) from the studies included in the analysis focused on the technical aspect; a table with related technical information is given in *Supplementary Material C*. A relatively small number of studies conducted environmental (9 out of 61) and economic assessments (4 out of 61). There was also a small number of studies that investigated the FLW-derived bioplastics from a multidimensional perspective, e.g., techno-economic (6 out of 61), environmental and economic (3 out of 61) and full sustainability (i.e., environmental, economic and social aspects) (3 out of 61) assessments.

The grouping of the eligible studies based on sustainability perspective, stage of the food value chain that FLW type belongs to, and biopolymer according to this systematic evidence mapping is presented in Figure 3.

Using the conceptual framework of [2] developed based on the CVORR analytical approach [39,40], we mapped the sustainability performance of FLW-derived bioplastics across all stages of their lifecycle, from raw materials acquisition to production, use, and end-of-life (EoL) management. Quantitative data from studies that carried out life cycle assessments (LCA) and economic assessments are provided in *Supplementary Material D*. Carbon emissions have been studied across the bioplastics lifecycle, whereas other environmental impact categories have received less attention.

It is worth noting that the study of environmental impacts is restricted to the acquisition/production stage (usually reported together) with only some glimpses provided across all other stages of the FLW-derived bioplastics lifecycle (i.e., raw material acquisition and EoL). Evidence of economic performance is also limited to the production stage. Moreover, evidence on social impacts emerging from the broader adoption of bioplastics produced from FLW is minimal; with some references made to societal cost [42] and social acceptance of production plants [43,44].

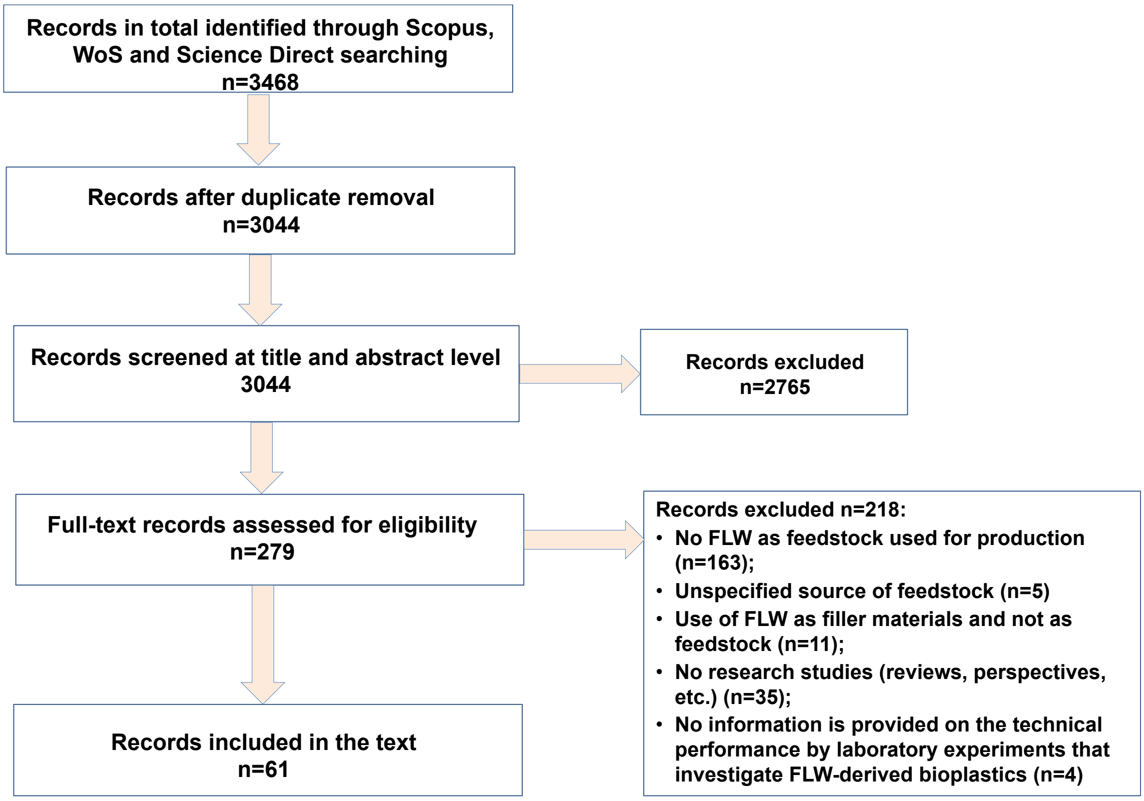


Figure 2. Flow diagram describing the results of searching and screening the literature on sustainability assessments of FLW-derived bioplastics.

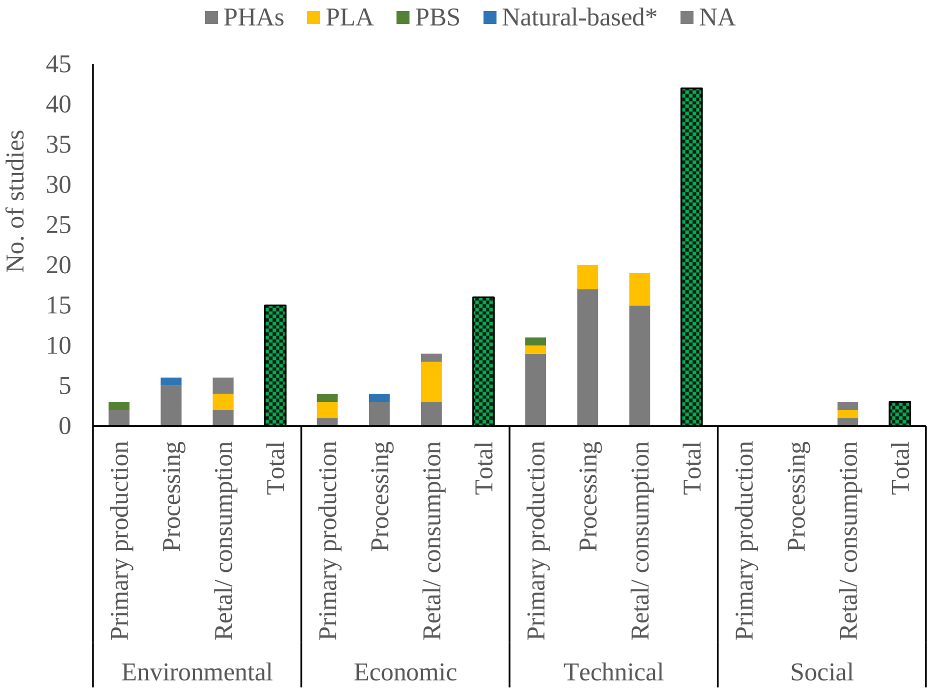


Figure 3. The number of eligible studies focusing on FLW-derived bioplastics grouped by the sustainability perspective (environmental, economic, technical and social), FLW feedstock based on the stage of the food value chain (primary production, processing and retail/consumption) and bioplastic type according to this systematic evidence map. (* Natural-based refers to polysaccharide- and protein-based polymers).

Due to the above limitations, acquisition and production (Section 4.1), as well as consumption-disposal and EoL management (Section 4.2) are jointly presented.

4.1. FLW Acquisition and FLW-Derived Bioplastics Production

The main positive environmental impact of using FLW as feedstock in bioplastics production is the recovery of FLW itself and its diversion from landfill which in the food waste management system is a certain route [45]. The use of FLW in bioplastics production displaces also the need for petrochemical-based plastics and this, in turn, results in multiple environmental benefits, a list of which is outlined in Table 2. However, there are still many uncertainties regarding the environmental performance of FLW valorisation, depending on the raw materials used (including chemicals), the number and type of processes employed and their energy requirements and associated carbon emissions [23,25,46].

In the economic domain, it is currently estimated to be more expensive to produce bioplastics than petrochemical-based plastics due to feedstock availability, collection/transportation and processing costs, regardless of whether 1st or 2nd generation feedstock is used [18,33]. However, some studies report that processing costs could be less for 2nd generation than for 1st generation feedstock (i.e., crop residues) [19,20,47,48] because of the latter's high acquisition cost (i.e., cultivation, harvesting, pre-processing) [2,10,12,27]. Nonetheless, technical aspects are the most complex, essential considerations at the production stage. Ensuring constant FLW feedstock availability and stable composition is essential for bioplastic production, [12], and thus, it could be an indicator of the economic viability of FLW-derived bioplastics. In turn, the type of FLW feedstock can impact the process employed for FLW-derived bioplastic production, as well as their properties and technical performance (see Table 2, the *end-product* consideration).

Table 2. Key considerations when assessing the sustainability performance of FLW-derived bioplastics at the raw material acquisition (RMA) stage and production (PROD) from a multidimensional perspective according to the eligible studies.

Considerations	*Aspect*	*Description*	*Lifecycle Stage*	*Amelioration*	*Reference*
1-6 ***Carbon emissions***	Env	Energy-intensive stages that seek to convert FLW into raw materials for bioplastics production.	RMA	1. Adoption of less energy-intensive processes (e.g., natural withering vs. thermal treatments, dissolved air floatation during extraction); 2. Use renewable resource-based energy systems.	[49–51]
Formation of degradation products	Env	Lignocellulosic biorefinery (e.g., furfural, hydroxymethylfurfural, phenolics, melanoidins, sugar degradation products) forms toxic by-products that inhibit fermentation.	PROD	Detoxicification process is needed to remove inhibitory compounds.	[52]
FLW transportation	Env	Long distances could lead to the degradation of FLW and the development of pathogens as well as considerable consumption of fossil fuels.	RMA	1. Transport in freezers—but environmentally is energy consuming; 2. Installation of valorisation processes near FLW production hubs (decentralised processes) 3. Reduce transportation distances;	[23,45,46,49]
Raw material use (e.g., chemicals and water)	Env	Halogenated and other organic solvents used to aid biopolymer recovery from cell material (e.g., through solvent extraction, selective dissolution and surfactant digestion) may pose occupational hazards; Requirements for water are relatively high.	PROD	1. Use of non-toxic raw materials during production (e.g., green solvents: CO$_2$ and dimethyl carbonate instead of NaOH and NaCl); 2. Increase solid organic rate—reduce the need for water dilution.	[13,25,43,49]
	Econ	Primary components required for the bioconversion (i.e., solvents, oxygen supply, chemicals to control the operating conditions, yeast extracts, strains for microbial culture (native vs. recombinant strains) and cultivation media).	PROD	1. Reduce the number of solvents during the extraction and purification; 2. Use of innate enzymes or mixed cultures.	[24,53,54]

Table 2. *Cont.*

Considerations	***Aspect***	***Description***	***Lifecycle Stage***	***Amelioration***	***Reference***
1-6 ***Waste generation***	Env, Econ	Considerable amounts of FLW residues could be generated due to the use of specific carbon sources for production, and by-products during extraction and purification could be generated.	PROD	1. Utilisation of FLW residues (by-products) needs to be explored; 2. Intergrade processes of biopolymer production with bioenergy; 3. Recovery of by-products produced; 4. Increase feedstock to product yield by optimising performance parameters (e.g., optimise growth and accumulation yields of PHA through proper pre-treatment (e.g., chemical vs. biological) and hydrolysis methods (e.g., acid vs. enzyme).	[13,45,51,55,56]
Cost-effectiveness	Econ	FLW availability and acquisition (storage and transportation) can affect operational process efficiency and economic effectiveness.	RMA	Installation of valorisation processes near FLW production and management hubs (e.g., large food processing plants, landfills, MSW sorting facilities).	[26]
	Econ	High moisture content impacts the energy intensity of pre-treatment processes.	RMA	1. Adoption of less energy-intensive processes; 2. Intergrade processes of biopolymer production with bioenergy.	[57]
Net present value (NPV)	Econ	Feedstock-to-product yield might be low depending on the source and composition of FLW (affected by geographical origin), type of biopolymer, production method, feeding regime, reactor conditions, and microbial strain (incl. assimilability by the microbes).	RMA, PROD	1. Separate collection of FLW; 2. Intergrade processes of biopolymer production with bioenergy; 3. Use of high-performance strains; 4. Upgrading the fermentation processes; 5. Harnessing the residual biomass (e.g., undigested waste from the enzymatic hydrolysis); 6. Content analysis of FLW substrates to identify components that improve bioconversion; 7. Optimising agitation speed to increase the oxygen transfer rate throughout the fermentation medium; 8. Select optimum pre-treatment, hydrolysis and extraction method in terms of production yields.	[25,43,55,56,58,59]
	Econ	Waste processing capacity (e.g., the number of batches, amount of feedstock and operation time) defines the economy of scale: the higher the processing capacity, the lower the production cost.	RMA, PROD	1. Ensuring predefined composition and constant quality of FLW; 2. Fine-tuning the supply of substrates through multi-stage continuous processes and proper feeding regimes; 3. Define clear business plans for commercialisation (considering market demand and feedstock availability).	[24,49,60–62]
Capital investment cost	Econ	Equipment, installations, instrumentations and buildings/facilities.	PROD	1. Implement high solid loadings; 2. Government funding; 3. Reduce process capacity equipment by selecting pre-treatment methods with minimum FLW loss during pre-treatment.	[24,55,63]
Utility costs	Econ	Energy-intensive processes (e.g., aeration, agitation, evaporation) and use of other resources (e.g., water) during pre-treatment, hydrolysis and fermentation.	RMA, PROD	1. Adoption of less energy-intensive processes; 2. Intergrade processes of biopolymer production with bioenergy; 3. Use of innate enzymes or mixed cultures.	[24,53,54]
FLW type (heterogeneity and composition)	Econ	The complexity of FLW composition has an impact on the energy pre-treatment and processing requirements and feedstock-to-product yield.	RMA, PROD	1. Separate collection of FLW; 2. Matching FLW type to different valorisation technology set-ups; 3. Using mixed microbial cultures.	[24,25,54,64]
	Tech	The carbon to nutrient (i.e., C/N) ratio of FLW might be lower than optimal, leading to metabolic blockage of substrate conversion.	RMA	Fine-tuning the C/N ratio for each bioconversion process depending on the feedstock, biopolymer type, and microbial strains.	[20,25,58]
	Tech	Constant feedstock quantity and quality (incl. composition) is a prerequisite for a successful valorisation process.	RMA	1. Separate collection of FLW; 2. Upgrade logistics of FLW management at the local level; 3. Fine-tuning the supply of substrates through multi-stage continuous processes and proper feeding regimes.	[26,49,62,65]

Table 2. *Cont.*

Considerations	*Aspect*	*Description*	*Lifecycle Stage*	*Amelioration*	*Reference*
1-6 ***End-product***	Tech	Feedstock: selecting appropriate substrates (or a combination of them) leads to the same polymers that display different properties.	RMA	1. Blending biopolymers to form biocomposites (still explored); 2. Use of natural additives, and compatibilisers; 3. Developing the product design and logistics; 4. Content analysis of FLW substrates to identify components that improve bioconversion; 5. Use of nanoparticles; 6. Chemical modification of polysaccharides.	[53,58,66–68]
	Tech	Production strategy: methods, operating conditions (i.e., pH, temperature, environment, culture age, nutrient restrictions, bioreactor configurations, hydraulic retention time, recirculation ratio), organic loading rate and feeding strategy determine the properties of bioplastics.	PROD	1. Fine-tuning the valorisation process to produce bioplastics needed in the market (e.g., through multi-stage continuous processes); 2. Developing the product design and logistics; 3. Improving extraction techniques and bioaugmentation of microbial strains.	[49,69]

Table 2 summarises the most important considerations. A detailed elaboration of some key environmental, economic and social impacts is provided further below.

4.1.1. Environmental Performance

Life cycle assessment (LCA) studies on FLW-derived bioplastics production that provide a comparison to 1st generation bioplastics and conventional plastics are limited [22,23,42]. Figure 4 compiled the evidence on the contribution of FLW-derived bioplastics production to global warming potential (GWP) from cradle-to-gate LCA studies, including available comparative evidence with 1st generation bioplastics and conventional plastics. For instance, a study reported that the use of agriculture crop residues (i.e., potato peels) in producing 2nd generation bioplastics contributes insignificantly to GWP, compared to the use of conventional plastics [22]. In contrast, another study reported that the production of PLA using FLW from the retail sector (i.e., 2nd generation) contributed to a higher GWP compared to that produced from corn-based feedstock (i.e., 1st generation) [42]. The authors of the study suggest that this is mainly due to process characteristics, the feedstock to product yield (i.e., low C6 sugar content in FLW used for PLA production) and the use of other ancillary materials [42].

Figure 4 also points to the difference in GWP between the use of FLW in producing bioplastics and the management of FLW via conventional waste management options. It is shown that carbon savings (or avoided carbon emissions) can only be accrued when FLW is diverted from a landfill. Carbon emissions were higher when anaerobic digestion (AD), composting and incineration with energy recovery were replaced by the use of FLW in production processes [42]. Notably, the integrated production of hydrogen and PHA from cheese whey underperformed compared to AD across all LCA impact categories. This considerable evidence points to the low technology readiness of FLW valorisation which leads to high pre-treatment requirements, low production yields and the high consumption of chemicals and energy during extraction [13,42]. However, technological advancements aimed at improving process efficiency and recovery rates and eliminating the use of chemicals and other resources (e.g., water and energy) are likely to reduce GWP by 179–210%, making FLW-derived bioplastics production more beneficial than the digestion of FLW in terms of GWP (41% lower than AD) [13].

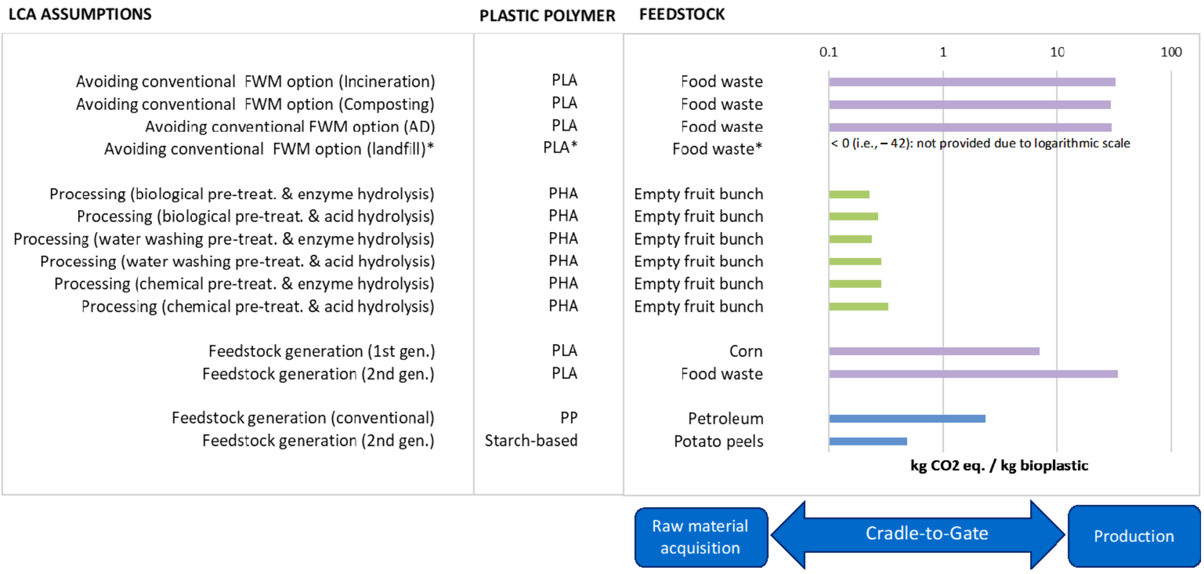


Figure 4. Carbon emissions (expressed in kg CO_2 eq./kg of end-product) reported by cradle-to-gate studies. Different colours in the bars indicate different studies. (* This is the only scenario with carbon savings (i.e., -42 kg CO_2 eq./kg of end-product) (Abbreviations: FWM: Food waste management; AD: Anaerobic digestion; gen.: generation; PP: Polypropylene; PLA: Polylactic acid; PHA: Polyhydroxyalkanoate).

The electricity input for the production of FLW-derived plastics, such as PHAs, is high [13,70]. As Koller et al. (2018) point this can contribute the most (79%) to the total ecological footprint of the PHA-production process due to a long fermentation period [46]. Therefore, the selection and set-up of the valorisation processes must be carefully tailored to the type of FLW, especially that of high moisture content. For example, a recent study found that the biological pre-treatment and enzyme hydrolysis were the best methods for valorising empty fruit bunch for PHA production, in terms of GWP [55].

Furthermore, studies reported that the transportation of FLW could negatively impact the environment [23,46,55]. Bishop et al. (2022) claimed that the decentralisation of bioplastics production from FW could reduce the GWP by 170% leading to negative environmental credit of -0.13 kg CO_2 eq./kg bioplastic [45]. Decentralised pre-treatment processes applied directly at the production sites (e.g., whey evaporation in the dairy industry before transportation) would substantially improve the environmental performance of the end product [23,45,46,51].

Evidence on other LCA impact categories is minimal. Related quantitative data is provided in *Supplementary Material D*. It is worth emphasising that chemicals (e.g., extraction solvents and acids during acid hydrolysis) typically used during the fermentation process may contribute to photochemical oxidation potential (POP), acidification potential and human toxicity and ecotoxicity [13,25,55]. The use of non-toxic raw materials during the production stage can significantly reduce potential harm [25]. Solvent leftovers after the extraction process are challenging to manage, creating environmental and health risks [34].

As reported by recent studies, the adoption of an integrated system for the simultaneous production of bioenergy (i.e., biogas and hydrogen) and biopolymer (i.e., PHAs) from FLW could provide environmental and economic benefits [56]. One such system is the anaerobic acidogenic fermentation of FLW (i.e., rice and dairy waste) to hydrogen and bioplastics precursors (e.g., organic acids such as lactic acid) production, followed by aerobic fermentation of the acids produced with the mixed microbial culture [71,72] or pure microbial culture [56] for PHA polymerisation. The use of an AD (i.e., acidic fermentation) to convert complex FLW to substrates (i.e., fermented streams) with a relatively constant composition of organic acids, enables relatively high bioplastics production yields [62].

For instance, the production efficiency of PHAs from unfermented FLW under anaerobic conditions was higher (ca. 10% higher production) than under aerobic conditions [71].

In addition, another study discussed the bioconversion of biogas into PHAs, reporting that it may provide environmental benefits compared to biogas production for combined heat and power (CHP) due to avoiding SO_2 and NO_2 emissions [43]. However, under the current technological advancements, biogas combustion performs better in terms of resource recovery due to lower land requirements, water consumption, fewer material needs and energy use [43].

4.1.2. Economic Performance

As outlined in Table 2, important economic considerations associated with FLW-derived bioplastics include cost-effectiveness, the net present value (NPV), the capital and operating cost, the FLW type and waste generation during production. The extraction and purification processes are essential stages of the biorefinery processes and, thus, add to the capital investment cost (pre-treatment and valorisation process). Most importantly yet, economic viability is intertwined with technical feasibility, as the latter is a key determinant to achieving high process efficiency and good production yields.

The capital investment cost is a critical factor in the economic viability of FLW-derived bioplastics production [24,55,61]. High capital and operational costs (e.g., utilities and primary components required for bioconversion), with low-profit margins due to low production yields and selling price of bioplastics, affect the annual revenue generation and payback time [73]. These cot-related challenges can make FLW valorisation processes an uneconomical venture, unless other sources of revenues or government funding are pursued, which can alleviate the cost [24]. For example, chemical pre-treatment of lignocellulosic FLW (i.e., empty fruit bunch) leads to a higher loss of feedstock during washing compared to biological and water washing pre-treatment methods making the requirements for capacity process equipment higher for the production of a specific amount of PHA [55]. At the same time, the cost arising from chemicals acquisition and the management of by-product generation affects the selling price of FLW-derived bioplastics [34]. However, by-products can be recovered for several applications increasing the profitability of biorefinery processes, e.g., biodiesel sector, animal feeding, AD, and additional production of value-added chemicals [45,73]. An economic assessment for the production of PLA from FLW reported that the sales of PLA contributed 57% to the annual revenue of the plant, whereas the sales of the by-products (lipids to biodiesel manufacturers and protein-rich solids for animal feed production) contributed nearly 40% to the annual revenues [24]. It must also be noted that a source of annual production plant revenues comes from tipping fees since they provide FLW management services [24].

The geographical origin was also found to be a crucial factor to the selling price of end-product [60]. For instance, FLW composition varies between places and this can affect the production yield [60], assuming that the valorisation process used and processing capacity could remain the same. In some cases, the process may need to cater for the changing composition of FLW (e.g., via introducing a pre-treatment process or using chemicals) which can bring up the capital and operational costs. At the same time, energy provision and feedstock availability can affect utilities and transportation costs, respectively [74]. Using FLW fractions, such as waste cooking oil, that do not require extensive pre-treatment processes before bioconversion can be a more financially attractive option [58]. Moreover, electricity prices can considerably differ from one region to another, affecting the biopolymer production cost [75]. For example, in regions with high electricity prices, biopolymer production might not be economically feasible (negative NPV). The selling price of FLW-derived bioplastics can be lowered by increasing the operational time, feedstock availability for conversion and market demand [59].

Adopting an integrated process that combines energy recovery with FLW biorefinery is a potential solution to be economically profitable [75]. Integrating processes for biofuel and FLW-derived bioplastics production provides simultaneous production of value-added products leading to lower selling prices of FLW-derived plastics [56,60,63], although evidence is still minimal. A recent economic assessment found that the conversion of FLW into value-added products (e.g., VFAs and PLA) is more profitable than their conversion into fuels [64]. Nevertheless, the recent techno-economic analysis showed that the selling price of PHAs (i.e., 4.83 $/kg) obtained from an integrated process remains higher than that of conventional plastics (polyolefin: 1.52–1.78 $/kg) [60].

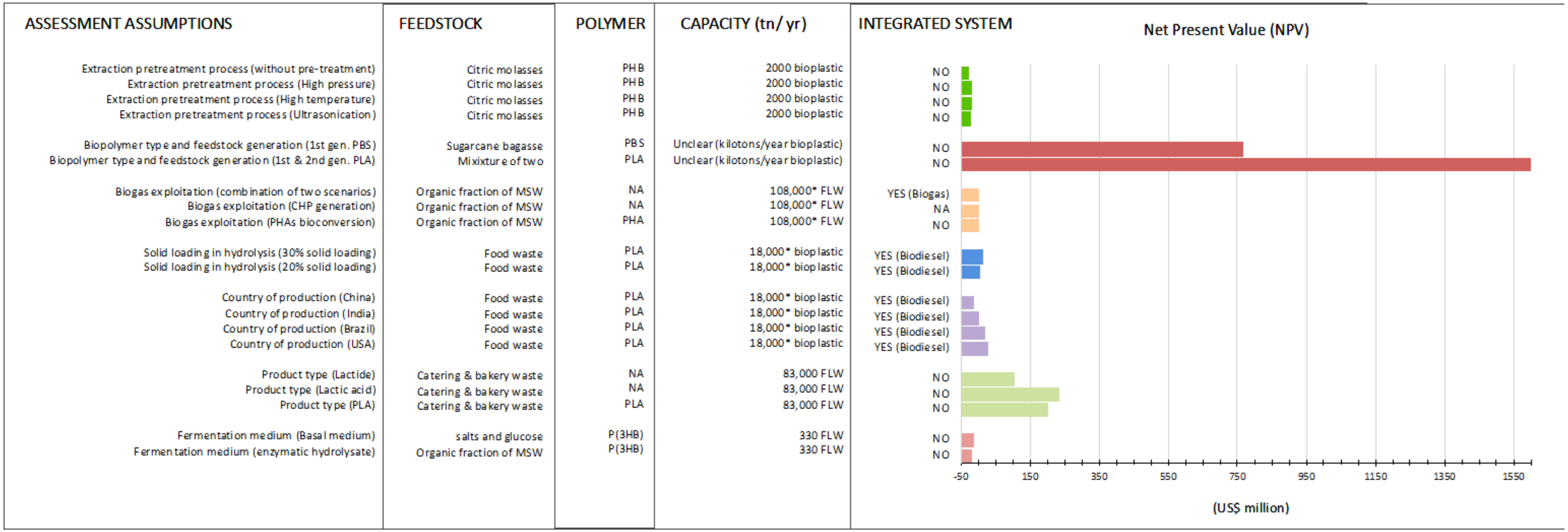
Furthermore, the economic performance of using the same FLW feedstock in producing different biopolymer types varies [59]. For example, the economic performance of PLA production with that of PBS using sugarcane bagasse was better than that of PBS production. PLA's economic performance was better due to a combination of factors, including, lower energy demands (i.e., PLA's heating demand was 8.18 as opposed to 5.80 MJ/kg of PBS), higher production rates and fewer processing steps (i.e., PBS consists of two fermentation processes of both succinic acid and 1,4-butanediol) [59].

Contrariwise, the economic performance of producing the same biopolymer from different FLW types also varies. When complex and heterogeneous substrates are used, such as industrial food waste, or food waste generated by households that consist of a mixture of compounds, the cost-effectiveness of bioplastics production varies widely [25]. A recent economic assessment for the production of PLA from different agro-industrial residues (i.e., sugarcane bagasse and coffee cut stems) found that the use of coffee cut stems as feedstock material can be economically feasible (i.e., >0 NPV). In contrast, sugarcane bagasse was not economically successful due to its high moisture content and low potential for fermentable sugar [57].

Despite the factors mentioned above, several other factors can affect the production yields and, therefore, the economic performance of FLW-derived bioplastics. These factors include fermentation medium [25,73,76], microbial culture system [53], feeding regime [65] and hydrolysis method [55]. Detailed information on these factors is provided in *Supplementary Material E*.

Figure 5 provides evidence from eligible economic assessments on the return on investment (ROI), production cost, NPV and selling price of bioplastics produced by FLW. It shows that changes in waste pre-treatment requirements [26,55], solid loadings during hydrolysis [63] and routes for product recovery [61] affect the economic viability of FLW-derived bioplastics.

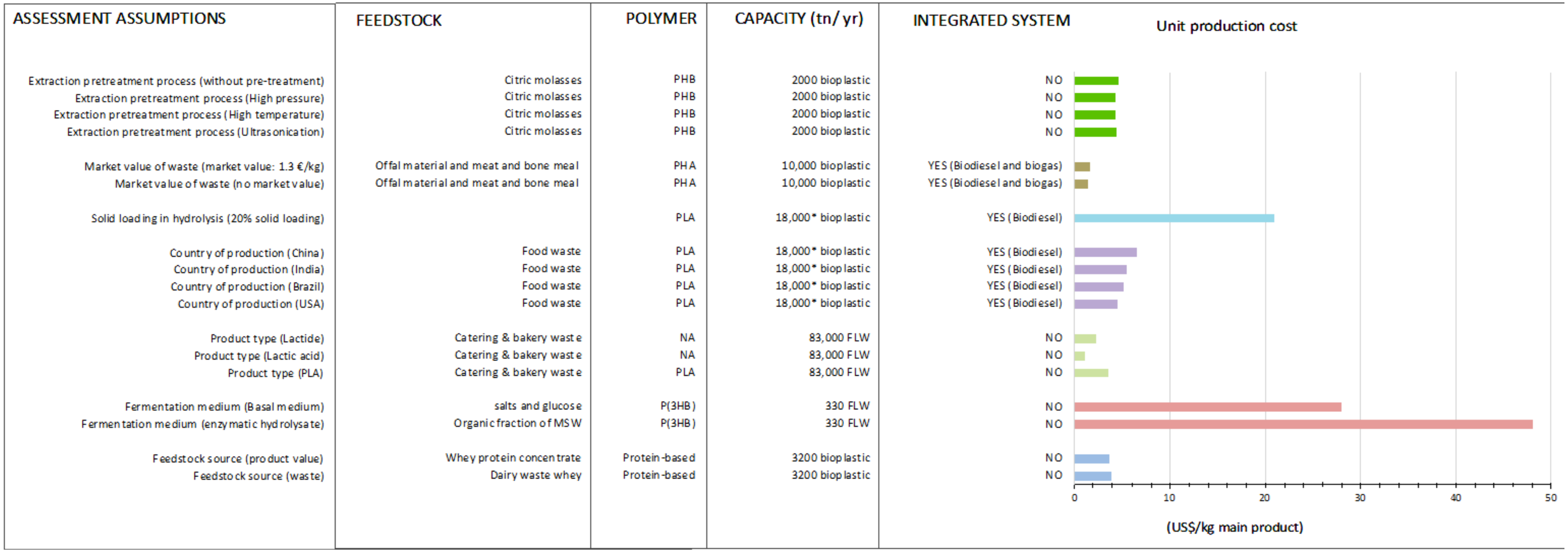
(**A**)



ASSESSMENT ASSUMPTIONS	FEEDSTOCK	POLYMER	CAPACITY (tn/ yr)	INTEGRATED SYSTEM
Extraction pretreatment process (without pre-treatment)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (High pressure)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (High temperature)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (Ultrasonication)	Citric molasses	PHB	2000 bioplastic	NO
Biopolymer type and feedstock generation (1st gen. PBS)	Sugarcane bagasse	PBS	Unclear (kilotons/year bioplastic)	NO
Biopolymer type and feedstock generation (1st & 2nd gen. PLA)	Mixixture of two	PLA	Unclear (kilotons/year bioplastic)	NO
Biogas exploitation (combination of two scenarios)	Organic fraction of MSW	NA	108,000* FLW	YES (Biogas)
Biogas exploitation (CHP generation)	Organic fraction of MSW	NA	108,000* FLW	NA
Biogas exploitation (PHAs bioconversion)	Organic fraction of MSW	PHA	108,000* FLW	NO
Solid loading in hydrolysis (30% solid loading)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Solid loading in hydrolysis (20% solid loading)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (China)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (India)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (Brazil)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (USA)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Product type (Lactide)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (Lactic acid)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (PLA)	Catering & bakery waste	PLA	83,000 FLW	NO
Fermentation medium (Basal medium)	salts and glucose	P(3HB)	330 FLW	NO
Fermentation medium (enzymatic hydrolysate)	Organic fraction of MSW	P(3HB)	330 FLW	NO

Figure 5. *Cont*.

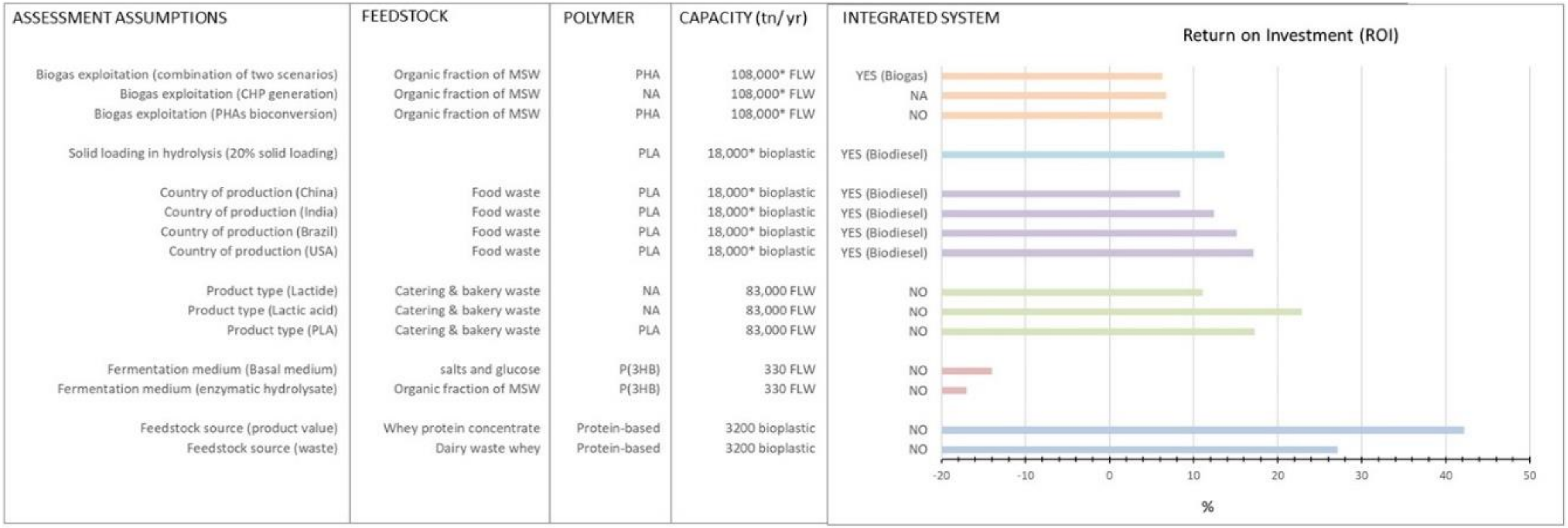
(B)



ASSESSMENT ASSUMPTIONS	FEEDSTOCK	POLYMER	CAPACITY (tn/yr)	INTEGRATED SYSTEM
Extraction pretreatment process (without pre-treatment)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (High pressure)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (High temperature)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (Ultrasonication)	Citric molasses	PHB	2000 bioplastic	NO
Market value of waste (market value: 1.3 €/kg)	Offal material and meat and bone meal	PHA	10,000 bioplastic	YES (Biodiesel and biogas)
Market value of waste (no market value)	Offal material and meat and bone meal	PHA	10,000 bioplastic	YES (Biodiesel and biogas)
Solid loading in hydrolysis (20% solid loading)		PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (China)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (India)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (Brazil)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (USA)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Product type (Lactide)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (Lactic acid)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (PLA)	Catering & bakery waste	PLA	83,000 FLW	NO
Fermentation medium (Basal medium)	salts and glucose	P(3HB)	330 FLW	NO
Fermentation medium (enzymatic hydrolysate)	Organic fraction of MSW	P(3HB)	330 FLW	NO
Feedstock source (product value)	Whey protein concentrate	Protein-based	3200 bioplastic	NO
Feedstock source (waste)	Dairy waste whey	Protein-based	3200 bioplastic	NO

Figure 5. *Cont.*

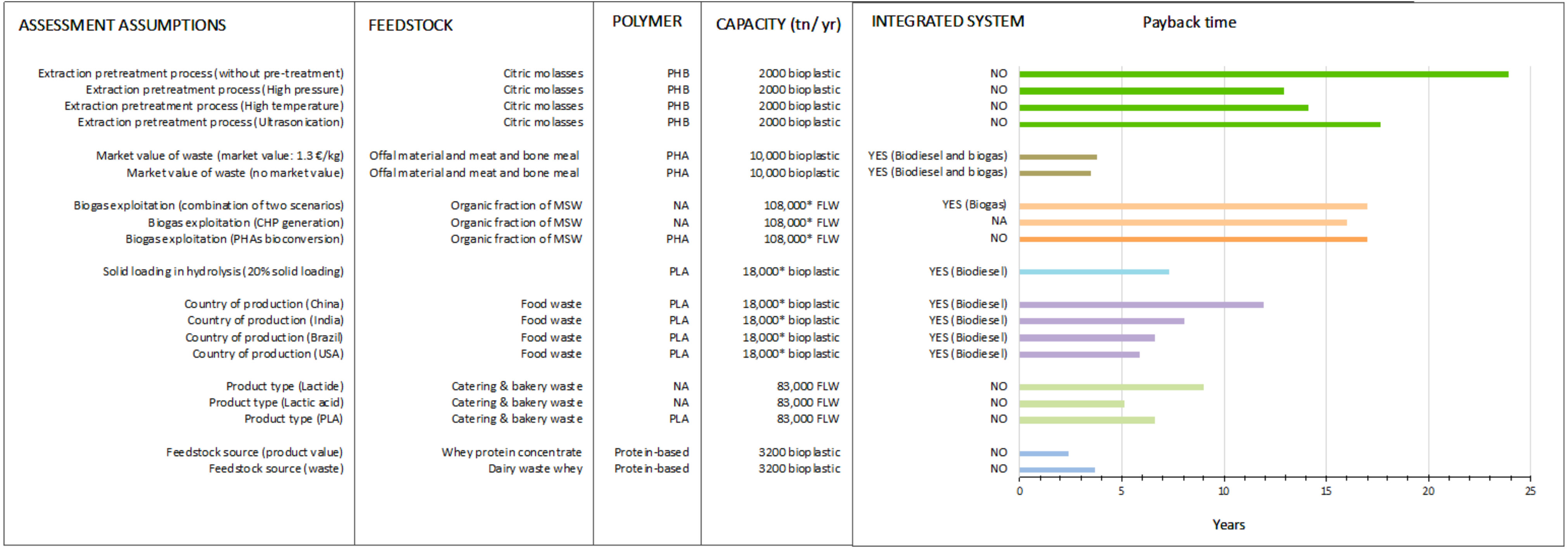
(**C**)



ASSESSMENT ASSUMPTIONS	FEEDSTOCK	POLYMER	CAPACITY (tn/yr)	INTEGRATED SYSTEM
Biogas exploitation (combination of two scenarios)	Organic fraction of MSW	PHA	108,000* FLW	YES (Biogas)
Biogas exploitation (CHP generation)	Organic fraction of MSW	NA	108,000* FLW	NA
Biogas exploitation (PHAs bioconversion)	Organic fraction of MSW	PHA	108,000* FLW	NO
Solid loading in hydrolysis (20% solid loading)		PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (China)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (India)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (Brazil)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (USA)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Product type (Lactide)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (Lactic acid)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (PLA)	Catering & bakery waste	PLA	83,000 FLW	NO
Fermentation medium (Basal medium)	salts and glucose	P(3HB)	330 FLW	NO
Fermentation medium (enzymatic hydrolysate)	Organic fraction of MSW	P(3HB)	330 FLW	NO
Feedstock source (product value)	Whey protein concentrate	Protein-based	3200 bioplastic	NO
Feedstock source (waste)	Dairy waste whey	Protein-based	3200 bioplastic	NO

Figure 5. *Cont*.

(**D**)



ASSESSMENT ASSUMPTIONS	FEEDSTOCK	POLYMER	CAPACITY (tn/ yr)	INTEGRATED SYSTEM
Extraction pretreatment process (without pre-treatment)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (High pressure)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (High temperature)	Citric molasses	PHB	2000 bioplastic	NO
Extraction pretreatment process (Ultrasonication)	Citric molasses	PHB	2000 bioplastic	NO
Market value of waste (market value: 1.3 €/kg)	Offal material and meat and bone meal	PHA	10,000 bioplastic	YES (Biodiesel and biogas)
Market value of waste (no market value)	Offal material and meat and bone meal	PHA	10,000 bioplastic	YES (Biodiesel and biogas)
Biogas exploitation (combination of two scenarios)	Organic fraction of MSW	NA	108,000* FLW	YES (Biogas)
Biogas exploitation (CHP generation)	Organic fraction of MSW	NA	108,000* FLW	NA
Biogas exploitation (PHAs bioconversion)	Organic fraction of MSW	PHA	108,000* FLW	NO
Solid loading in hydrolysis (20% solid loading)		PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (China)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (India)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (Brazil)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Country of production (USA)	Food waste	PLA	18,000* bioplastic	YES (Biodiesel)
Product type (Lactide)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (Lactic acid)	Catering & bakery waste	NA	83,000 FLW	NO
Product type (PLA)	Catering & bakery waste	PLA	83,000 FLW	NO
Feedstock source (product value)	Whey protein concentrate	Protein-based	3200 bioplastic	NO
Feedstock source (waste)	Dairy waste whey	Protein-based	3200 bioplastic	NO

Figure 5. *Cont*.

(**E**)

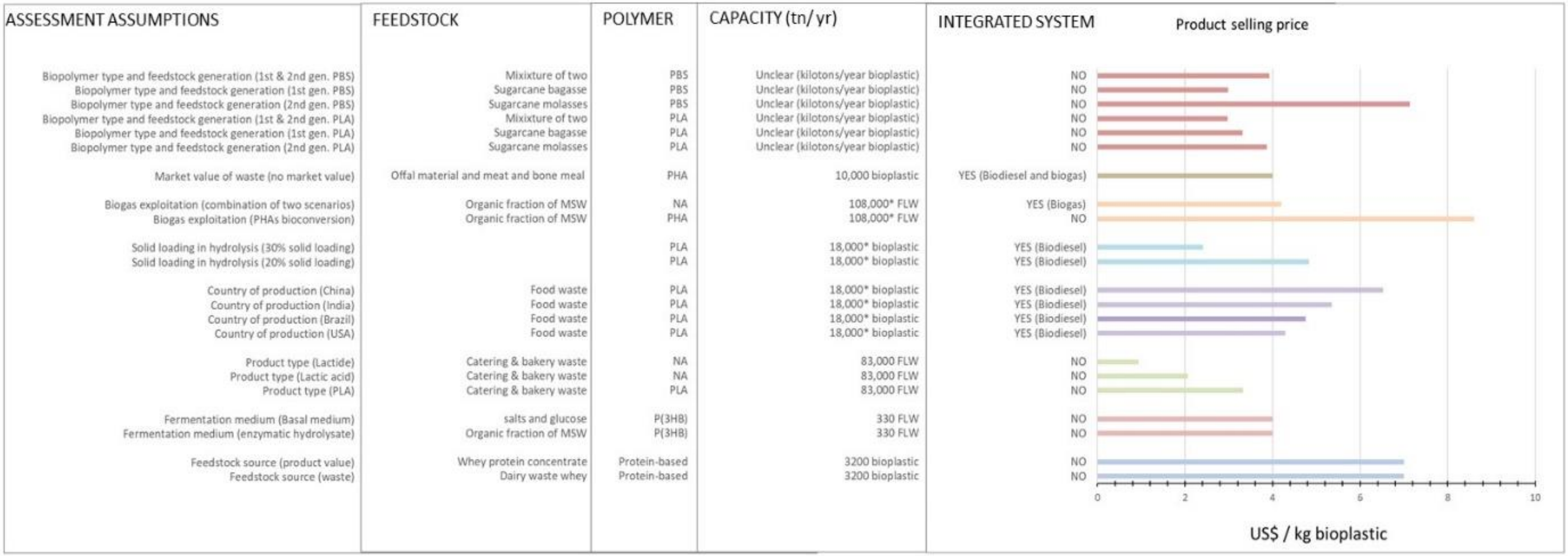


Figure 5. Economic indicators used to assess the economic performance of the production of FLW-derived bioplastics: (**A**) Net Present Value (NPV); (**B**) Unit production cost; (**C**) Return on Investment (ROI); (**D**) Payback time; (**E**) Product selling price. Different colours in bars indicate different studies (Capacity refers to the processing capacity of the plant: * the capacity was converted from tn/day into t/year assuming that the plant operation was 360 days per year for better comparison).

4.1.3. Technical Performance

Technical parameters such as the type and amount of carbon source and availability of nutrients affect the composition of bioplastics and their functional characteristics, as outlined in Table 2 [67,73]. For example, 1 kg of bioplastic production needs around 12–130 kg of FLW depending on the production efficiency and FLW type [13,42]. PHAs production from waste cooking oil [38,58,77–80] received attention due to several legislative restrictions on its management [81], the vast amounts of waste oil generated in food processing industries and the hospitality sector every year, and its relatively homogeneous composition, that make it an attractive substrate [16,82]. The use of waste frying oils as a carbon source for producing PHAs can lead to higher production yields than pure/fresh vegetable oil because of the higher percentages of free fatty acids [80]. Even though prolonged oil heating may change the composition and reduce the amount of unsaturation, which could inhibit the bioconversion process, it contains residual carbohydrates, proteins and fats from the food that can be easily metabolised, leading to higher production yields, which are reported as interactions of food and moisture with oil [58].

Animal by-products are also considered valuable carbon sources for the production of PHAs [49,73]. Lipid substrates can be stored at a cooling temperature for relatively long periods without additional precautions to suppress microbial decomposition [83]. The EU-funded project ANIMPOL (biotechnological conversion of carbon-containing wastes for eco-efficient production of high-value products) established a biotechnological process to convert residues from animal-processing, rendering and biodiesel industries into biodegradable polymeric materials (i.e., PHAs) [84]. The process has received increased attention from researchers [49–51,73,83].

Moreover, Yu, Chua, Huang, Lo and Chen [66] found that the texture of biopolymers produced entirely by butyric acid was brittle. Replacing butyric acid with valeric acid can produce a more elastic and softer biopolymer (malt wastes from a beer brewery used as feedstock) [66]. Additionally, the production strategy and operating conditions affect the molecular mass of bioplastics produced and therefore their properties [11]. Attention was paid to natural additives such as plasticisers, binding agents [68] and antioxidants (e.g., polyphenols, flavanols and tannins) [85]. The most common are glycerol, derived from the hydrolysis of fats and oils, and sorbitol, obtained from fruits and cellulose, which can be extracted from a wide variety of organic materials [68]. For example, blending PHAs with polyethylene glycol (PEG) can significantly improve the poly(3-hydroxybutyrate) (P3HB)/PEG films surface morphology, hydrophilicity, protein adsorption and in vitro cytocompatibility [53].

4.2. Consumption and EoL Management

Evidence on FLW-derived bioplastics use and EoL management is sparse. Specifically, at the consumption stage, there is no evidence available on the environmental or economic performance of FLW-derived bioplastics, as they are still at the laboratory scale. At the EoL stage, evidence exists mainly for 1st generation of bio-based biodegradable plastics that have similar characteristics with FLW-derived bioplastics in terms of biodegradability potential and source of raw materials (i.e., biomass). However, extrapolating information from 1st generation bioplastics might be misleading since the best EoL option may considerably differ from product to product [86].

A recent study calculated the GWP of PLA produced from organic waste (potentially FLW) considering the EU-average EoL split for rigid packaging (i.e., 60% recycling, 21% incineration and 19% landfilling) implying that GWP induced by PLA at its EoL stage is significantly higher than that of recycled high-density polyethylene (HDPE), bio-based HDPE of 1st generation and virgin HDPE mainly due to heating consumption during reprocessing [87]. Another cradle-to-grave LCA study showed that 2nd generation bioplastics (i.e., bio-PBS from crop residues) contributed less to GWP compared to 1st generation bioplastics (i.e., bio-PBS from energy crops), conventional plastics (PP, PE, and PET) and partly 1st and partly 2nd generation bioplastic (i.e., bio-PBS from bio-based succinic acid and fossil fuel-based 1,4 butanediol) [23]. However, it is unclear on how the decision-making process concerning the assumptions (i.e., conservative vs. optimistic) was carried out. These comparative results are presented in Figure 6. Carbon emissions in Figure 6 do not consider the stage of use, assuming that impacts are negligible.

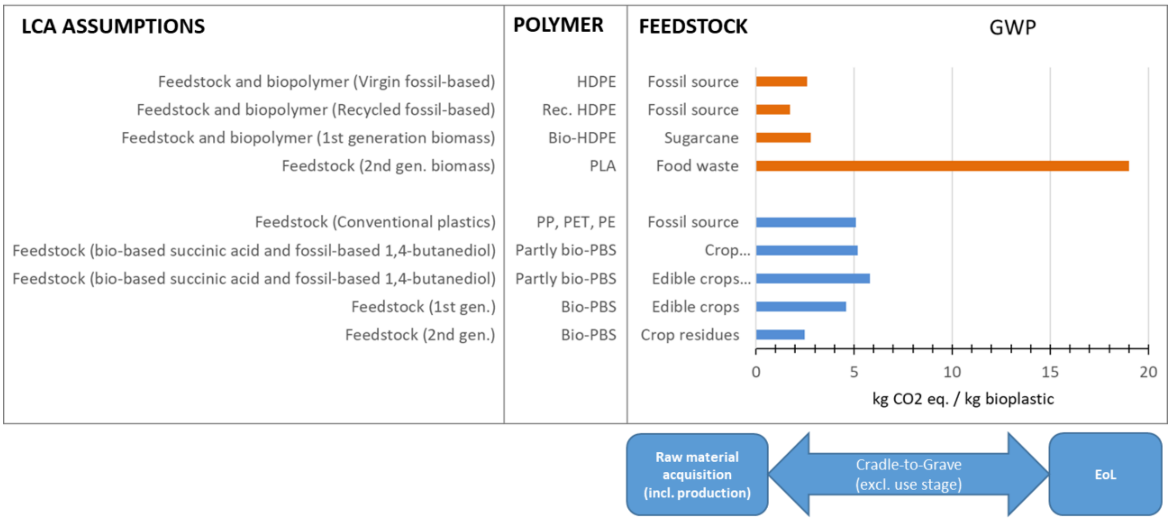


Figure 6. Carbon emissions (expressed in kg CO_2 eq./kg of end-product) induced FLW-derived bioplastics lifecycle including quantitative data from cradle-to-grave studies included in this systematic evidence mapping. Different colours in the bars indicate different studies.

It must be noted that the functional unit was 1 kg of plastic. Yet, it is worth noting, that in interpreting evidence making sense of the functional unit is critical. For instance, conventional plastics typically have a lower density than bio-based plastics. Therefore, the higher mass of bio-based plastics is needed to fulfil the same functions as conventional plastics. However, there is currently no sufficient evidence to determine the exact ratio, as its estimation depends on the mechanical, thermal and barrier properties of polymers, including the number of additives and fillers used to produce the final plastic articles [23].

Currently, there is no evidence to support the ability of FLW-derived bioplastics to be disposed of and managed with other recyclable waste streams. Their recyclability remains a blind spot that should be considered in sustainability assessments [2]. Regarding thermal treatment, the fact that FLW-derived bioplastics are bio-based indicates their carbon neutrality during incineration [68]. In principle, FLW-derived bioplastics could be managed via conventional organic waste recycling routes, such as composting (i.e., nutrient recovery and carbon sequestration) and AD (i.e., renewable energy recovery and prevention of fossil fuel depletion). However, the variability in biodegradation rates of the different types of FLW-derived bioplastics could render their management via organic waste recycling processes quite challenging and is a topic of urgent investigation [88]. The rate of biodegradation depends on the characteristics of biopolymers such as monomeric composition, side chain, and crystallinity, but is also affected by environmental conditions, such as temperature, moisture content, nutrient availability, and density of microbial population that have remained underexplored [82]. A cradle-to-grave LCA study reported that the GWP of diverting 100% of FLW-derived bioplastics into AD delivers the best outcome (i.e., -0.003 kg CO_2 eq./kg bioplastic) compared to composting (0.22 kg CO_2 eq./kg bioplastic) and incineration (0.24 kg CO_2 eq./kg bioplastic) [45].

Finally, FLW-derived bioplastics littering could be worse than thatconventional plastics. Their uncontrolled disposal in the environment may lead to the accumulation of fragmented microplastics since their complete degradation in the natural environment may never be achieved [31].

5. Discussion

The status quo of FLW-derived bioplastics is hard to decipher. Evidence on FLW-derived bioplastics sustainability is scattered across the plastics value chain, obscuring the generation of robust insights. This is attributed to the wide variety of FLW substrates, end-products, production media and assumptions made in this field, which make it difficult to generate any clear insights [89]. Albeit, the limited evidence, it is clear that research attention has been placed primarily on the production stage, while evidence at the consumption and EoL stages is lacking.

Producing bioplastics for FLW is beyond ideal. At the stage of raw material acquisition, the optimisation of FLW pre-treatment processes, and the inherent heterogeneity of FLW are key requirements for ensuring sustainable FLW-derived bioplastics production considering both, temporal and spatial variations. Feedstock availability, composition and seasonality make FLW valorisation challenging [90]. A homogenous feedstock may lead to the production of biopolymers with consistent quality and properties [33]. Hence, it would not be surprising if there is an increased focus on FLW from the primary production (farm) and food processing industry that could secure a more stable and homogeneous feedstock than FLW from the hospitality and household sectors [10]. Removing reliance on FLW feedstock generated in the hospitality and household sectors also eliminates risks associated with non-food residues and impurities that could negatively impact the process performance [34], and reduces the need for intensive pre-treatment processes at the biorefinery facilities.

The use and EoL stages of the FLW-derived bioplastics lifecycle are overlooked and this entails multi-dimensional risks (i.e., risks that span across environmental, economic, social and technical domains). For instance, the use of chemicals to give FLW-derived bioplastics specific properties and associated safety concerns of their application in the food packaging sector have yet to be investigated [91]. At the same time, their biodegradability potential in all environmental compartments must be assessed as it may pose additional risks at the EoL stage leading to unintended consequences [92,93]. To ensure multi-dimensional risks are eliminated there is a need to fully understand FLW-derived bioplastics properties (i.e., compositional, contextual and dynamic) and behaviour across their lifecycle [94].

Notwithstanding, the use of FLW in bioplastics production is a unique opportunity to address problems in both the food and plastics systems. The investigation of this potential alone is worthwhile and exciting as there is no single end product from FLW; multiple pathways can be adopted for FLW processing leading to a multitude of end products and by-products that could deliver value in our system. The selection of the valorisation process (and by extension of the end product) needs to be aligned with market demand, feedstock availability and stability (present and the future), and with infrastructural and regulatory landscapes; making this a thrilling exploration. Still, assessing the sustainability of acquisition and production, and even more so of the use and EoL fate of FLW-derived bioplastics is the most challenging part of this endeavour and a determining factor in streamlining FLW-derived bioplastics.

Social impacts associated with FLW-derived bioplastics are the least investigated area. However, consumers' environmental concerns and regulatory restrictions over petrochemical-based plastics are predicted to boost demand for bioplastics. These concerns and awareness, coupled with consumers' willingness to pay higher for bioplastic products point to the fact that FLW-derived bioplastics may become the solution of the future [18]. There are two aspects that could influence the public acceptance of FLW-derived bioplastics: (i) the construction of FLW valorisation facilities since history showed that the construction of thermal energy technologies was negatively perceived; (ii) and the use of animal-derived feedstock for bioplastics production [92]. In a similar vein, the use of FLW in producing bioplastics is quite complex from a regulatory perspective, as end-of-waste criteria must be established for its use. End-of-waste criteria laid down in Article 6 of [95] refer to conditions that must be fulfilled for waste to achieve a non-waste status through a recovery operation reflecting human health and environmental protection as well as economic and environmental benefits [96]. So far, end-of-waste criteria have been laid down by the Commission for specific waste streams (i.e., iron, steel and aluminium scrap, glass cullet and copper scrap) [96], while criteria also need to be developed for each product category including FLW substrates for bioplastics production. For example, a draft proposal on end-of-waste criteria for cheese whey in the Greek market is provided for two applications: animal feed and extraction of functional ingredients [97]. Still, related proposals for bioplastics production are missing.

The integration of policy with practice points to a careful consideration of the potential applications and limitations of FLW-derived bioplastics across their lifecycle. Investments in infrastructure [90] supported by the policy are essential for enabling growth, but to ensure long-term growth such investments must be backed up by holistic life cycle sustainability assessments [29,98]. Potential commercialisation of FLW-derived bioplastics that are not holistically assessed on their sustainability potential could bolster the industry's claim to green and sustainability credentials, whilst creating negative unintended consequences at the EoL stage and the food system. While FLW-derived bioplastics production is at an embryonic stage, the rapid technological advancement of biorefineries for FLW valorisation in the last decade signals that the pace of progress may well be on an increasing trajectory.

To that end, a synergistic collaboration among direct (i.e., food and plastic industry) and indirect stakeholders (i.e., researchers and policymakers) could ensure calculated and informed steps towards generating sustainable solutions that can benefit the plastic value chain, instead of making it more congested and cumbersome. Genetic engineering [37,82], biorefinery platforms [34] and the recyclability potential of bioplastics [12,36] could potentially optimise FLW-derived bioplastics production pathways [30].

Finally, we must not lose sight of the need to achieve sustainability; as pointed out by Gerassimidou et al. (2021) emphasizing technological innovation to promote the substitutability of petrochemical-based plastics, bears the risk of de-emphasising the need to address the problem at its roots, i.e., reducing the number of plastics made and placed on the market [2]. To indicate what is feasible, reasonable and practicable to achieve now and in the future, there is a need to understand societal needs alongside the ability to produce, use and manage FLW-derived bioplastics in a way that is sustainable and safe for the environment and society. This is what makes the potential of using FLW in bioplastics production a truly innovative solution.

6. Conclusions

This work assesses the potential of producing bioplastics from food loss and waste—hence, FLW-derived bioplastics—and offers a reality check over their life cycle sustainability performance. It is evident that while information on the sustainability potential of FLW-derived bioplastics is thinly dispersed across the plastics value chain, FLW-derived bioplastics production is imminent. Notwithstanding, lack of robust insights that could suggest that FLW-derived bioplastics are an environmentally friendly, economically viable and technically feasible solution that could lead to unintended consequences. At present the technological maturity of FLW valorisation is low, and the logistics are challenging demanding a tailored approach to valorisation process design and operation considering regional specificities, feedstock availability and infrastructural and regulatory landscape. This highlights the need for further research to ensure that FLW valorisation for bioplastics production is a sustainable, safe and transformative venture that could revolutionise both the food system and the plastics economy; not adding to the plastic pollution problem. At the same time, the stage of EoL of FLW-derived bioplastics has received limited to no attention; highlighting our inability to think of the end at the very beginning of any innovation and the imminent failure of our system to bring transformative change. To prevent such oversights, we need to employ a holistic, integrated approach to the assessment and evaluation of innovative solutions to make sure they deliver long-term benefits and reduce trade-offs. The fragmentation between assessment research and technological development is still very much of a barrier preventing truly sustainable changes to materialise. Learning from the past is key to ensuring that our future is on the right path of making decisions and generating solutions that are sustainable and safe for the environment and society at large.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15010611/s1, Supplementary material section A: List of search terms and strings used in this systematic evidence mapping, Supplementary material section B: Eligible studies of this systematic evidence mapping, Supplementary material section C: Eligible studies focused on the technical aspect of FLW-derived bioplastics, Supplementary material section D: Quantitative data obtained from sustainable assessments of FLW-derived bioplastics, Supplementary material section E: Influential factors on the economic performance of PHAs production from FLW.

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