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Attributional and consequential life cycle perspectives of second-generation polylactic acid: The benefits of integrating a recycling strategy

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ABSTRACT

The climate crisis calls for a shift from petrochemicals to bio-based products to reduce environmental consequences. Polylactic acid (PLA) is one of the most widely used biopolymers, due to its mechanical properties and renewable origin, to produce bio-based compostable plastic for food packaging. The objective of this study is to determine the environmental feasibility of a second-generation PLA production based on wheat straw; and the role of a chemical recycling plant on the environmental performance of a bioproduct at an early design stage. A holistic assessment was performed through the Life Cycle Assessment (LCA) methodology considering both attributional and consequential perspectives, through a cradle-to-grave approach. The attributional LCA results show that lactic acid production was the main contributor due to the wheat straw pre-treatment and downstream separation and purification (DSP) processes. The integration of a recycling plant leads to a significant reduction of burdens, ranging from 1.38 to 0.44 kg CO_2eq in the Global Warming category. Furthermore, consequential LCA results shows that the increased demand for substitute products for activities such as feeding, fertilisation and energy generation and the indirect emissions from land use change related to the conversion of land for the cultivation of raw materials are relevant factors in the environmental effects associated with the possible implementation of straw-based bioPLA production system.

1. Introduction

Plastics are the most widely used packaging material for food. In 2015, their estimated life-cycle greenhouse gas (GHG) emissions were about 1.7 Gt CO_2e and are expected to grow to 6.5 Gt CO_2e by 2050 (Zheng and Suh, 2019), due to the increasing food demand by the growing global population (Alexandratos and Bruinsma, 2012). The massive use of plastics leads to damage to marine and terrestrial ecosystems, as well as to human and animal health (Boots et al., 2019; Li et al., 2016). These widespread environmental consequences have motivated a negative societal perception towards single-use plastics from the petrochemical industry (Rochman et al., 2016).

Bioplastics, despite their nature as biopolymers, encompass non-degradable and durable plastics or plastics that are biodegradable (Soroudi and Jakubowicz, 2013). They are predominantly produced from first generation feedstocks such as maize, cane sugar, sugar beet, among others (Aryan et al., 2021). Thus, they appear as a potential solution to reduce fossil resource demand and decreasing environmental burdens at the end-of-life stage (Bishop et al., 2021a). Although bioplastics are currently accounting for around 1.5% of the total plastics market, with an estimate of 390 Mt (Plastics Europe, 2022), their demand is growing rapidly (Zhao et al., 2020). Global bioplastics production is expected to increase from about 2.2 to 6.3 million tons during the 2022–2027 period (European-bioplastics, 2022), promoting the transition towards a low-carbon economy and society.

Polylactic acid (PLA) is one of the most representative biopolymers with a worldwide production of around 460 thousand tonnes (European-bioplastics, 2022). PLA is a bio-based aliphatic polyester obtained from lactic acid (LA) using mainly starch feedstocks (Lim et al., 2008), and is commercially produced by industrial companies such as NatureWorks, Corbion and Futerro (E4tech, 2015). A broad set of industrial sectors are interested in PLA production, e.g., textiles, packaging, disposable cutlery, 3D printing, and drug delivery (DeStefano et al., 2020; Jamshidian et al., 2010). As PLA has the potential to replace

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petrochemical plastics, the identification of alternative sources that substitute feedstocks for human and animal food is essential. In addition, a major concern for bio-based products is the land use change required to meet the potentially growing demand. It is estimated that the conversion of natural landscapes to grow the required feedstock can lead to net GHG emissions of approximately 90–120 times greater than the annual emissions savings from substituting fossil-based products (Piemonte and Gironi, 2011). Consequently, GHG reductions could be achieved if non-food crops or residues (i.e., second-generation feedstock) are used to obtain these products, while also ensuring that they are properly recycled at the end of their useful life (EoL) (Aryan et al., 2021). Second-generation (2G) feedstocks (such as agricultural residues, wood, and energy crops) typically contain high levels lignocellulose (De Oliveira et al., 2020), with potential for PLA production.

Life cycle assessment (LCA) is a widely known methodology to estimate potential environmental burdens attributed to a product and service throughout its life cycle (ISO, 2006a, 2006b), also known as attributional LCA (A-LCA). This approach has been widely applied in the literature as a useful tool to determine the environmental feasibility of new bio-based products under an attributional perspective (Julio et al., 2017). This work addresses the environmental assessment of 2G PLA production from the valorisation of wheat straw as a source of fermentable sugars. The potential availability of the post-harvest wheat by-product would reach a total value of approximately 58 million tons in the European Union by 2030 (Hỳsková et al., 2020). Hence, straw may represent a valuable source for producing this biopolymer in a bioeconomy model, avoiding the food dilemma that represents its production from first-generation feedstocks. In this regard, previous studies have demonstrated the technical viability of the use of wheat straw for bioproducts, addressing the pre-treatment stage for fractioning the biomass until the intermediate products as the lactic acid required for the PLA production. Just to give some examples, Ballesteros et al. (2006) explored the steam explosion pre-treatment to obtain the fermentable sugars, Zhang et al. (2022) converted the straw into lactic acid under alkaline hydrothermal conditions, Ouyang et al. (2020) developed a one-pot process to produced lactic acid with an adapted *Bacillus coagulans*, and Guo et al. (2023) presented a catalyst for the hydrothermal conversion of wheat straw to also produce lactic acid.

Although the environmental burdens of the manufacturing of PLA have been previously investigated, for instance, from sugar beet pulp, corn stover (Ioannidou et al., 2022), wet waste feedstocks (Kim et al., 2022a), sugarcane and cassava (Changwichan et al., 2018; Papong et al., 2014), the promotion of biopolymers to replace fossil-based options entails environmental consequences that cannot be determined solely by an attributional LCA approach (Ögmundarson et al., 2020). A review article on bioplastics LCA (Bishop et al., 2021a) identified some relevant issues related to the environmental assessment of these products: i) many studies did not provide a holistic view of environmental burdens leading to potential erroneous conclusions; ii) lack of attention on the environmental consequences; and iii) indirect land use change (iLUC) has not been sufficiently addressed. In this regard, these are the research gaps that this work addresses through the environmental assessment of straw-based PLA production.

To determine the environmental effects of straw-based PLA system, the consequential LCA (C-LCA) perspective is used, as it describes the economic changes driven by the introduction of the analysed product system (Bjørn et al., 2018b; Brandão, 2022; Schaubroeck et al., 2021), and it is arguably the pertinent methodological approach to assess the decisions of replacing products (Bishop et al., 2021a). Consequential modelling uses marginal suppliers that may increase (or decrease) production due to an increase (or decrease) in demand for the product or process; as well as products and processes that will be replaced in other systems (i.e., system expansion) due to the production of additional co-products (Ekvall et al., 2016; Schaubroeck et al., 2021). In the context of bioplastics, consequential perspective has been less explored (Bishop et al., 2021a). Alvarenga et al. (2013) estimated the consequential burdens of bioethanol-based polyvinyl chloride (PVC) adding the effects of iLUC and avoiding the fossil-counterpart production; while Liptow and Tillman (2012) evaluated the impacts of sugarcane low-density polyethylene (LDPE) and compared them against fossil-based LDPE. Thus, the scarce consequential approach of bioplastics in the literature has been focussed on the displacement or substitution of their fossil-based counterpart. As the business-as-usual of PLA is based on first-generation feedstocks (i.e., maize), this research aims to provide first insights into the environmental effects of moving from 1G- and fossil-based production towards a second-generation PLA with a restricted feedstock as wheat straw, considering real scenarios substitution of this raw material.

This work addresses three objectives for a comprehensive assessment to provide clear evidence for the environmental feasibility of this product system: i) determine the environmental performance of 2G PLA production from wheat straw valorisation based on an A-LCA perspective, ii) identify the environmental implications of 2G PLA production through a C-LCA approach, evaluating traditional use scenarios of the straw and the restricted proportion of wheat straw in the market, and iii) recognise the benefits or drawbacks of integrating an end-of-life stage in the PLA biorefinery design, both in A-LCA and C-LCA perspectives. Thus, this research contributes to providing a wide environmental perspective of straw-based PLA, that besides estimating the attributional burdens, attempts to determine the potential environmental consequences of this product in the market. Furthermore, although this system could be considered a circular model as it valorises waste biomass, closing its loop can demonstrate the implications of integrating a recycling strategy early in the design phase to reduce resource depletion (and avoid agricultural activities) and identify possible trade-offs in the environmental burdens assessed. In this way, this research provides information to support the decision-making process around bioplastics deployment.

2. Methods

2.1. Aim and scope of the study

The first step in a LCA study is the definition of the objective pursued, accordingly, in this research the aims were the following:

- Determine the potential environmental burdens, from an attributional life-cycle approach, of the second-generation PLA production using wheat straw as feedstock.
- Determine the environmental consequences of using straw to produce 2G-PLA instead of using it for traditional activities such as animal feed, organic fertilisation, and heat generation. In this way, the production of both fossil counterpart and 1G-PLA could be avoided.
- Estimate the possible benefits and/or drawbacks of integrating a bioplastic recycling facility (in this case chemical recycling) at an early stage of the biorefinery design. Thus, recycled lactic acid will reduce the straw demand and resource consumption in the processes associated with the production of virgin lactic acid.

To carry out this work, the LCA methodology was applied following the ISO 14040 and 14,044 guidelines (ISO, 2006a, 2006b), considering a cradle-to-grave approach (see Fig. 1a). Therefore, processes from feedstock extraction, wheat cultivation, PLA production and the end-of-life stage (chemical recycling) were considered. The manufacturing and use stages were excluded from the analysis. The former because the uncertainty of the product made from PLA granulate, i.e., granulated into products such as films or trays (Bishop et al., 2021b). Moreover, studies claiming that the largest impacts of packaging product elaboration and disposal come from polymer extraction and granulate production (Ingrao et al., 2015). The second one (i.e., use phase) was excluded because its environmental impact is likely to be negligible (Ingrao et al., 2017). To report the environmental performance, 1 kg of

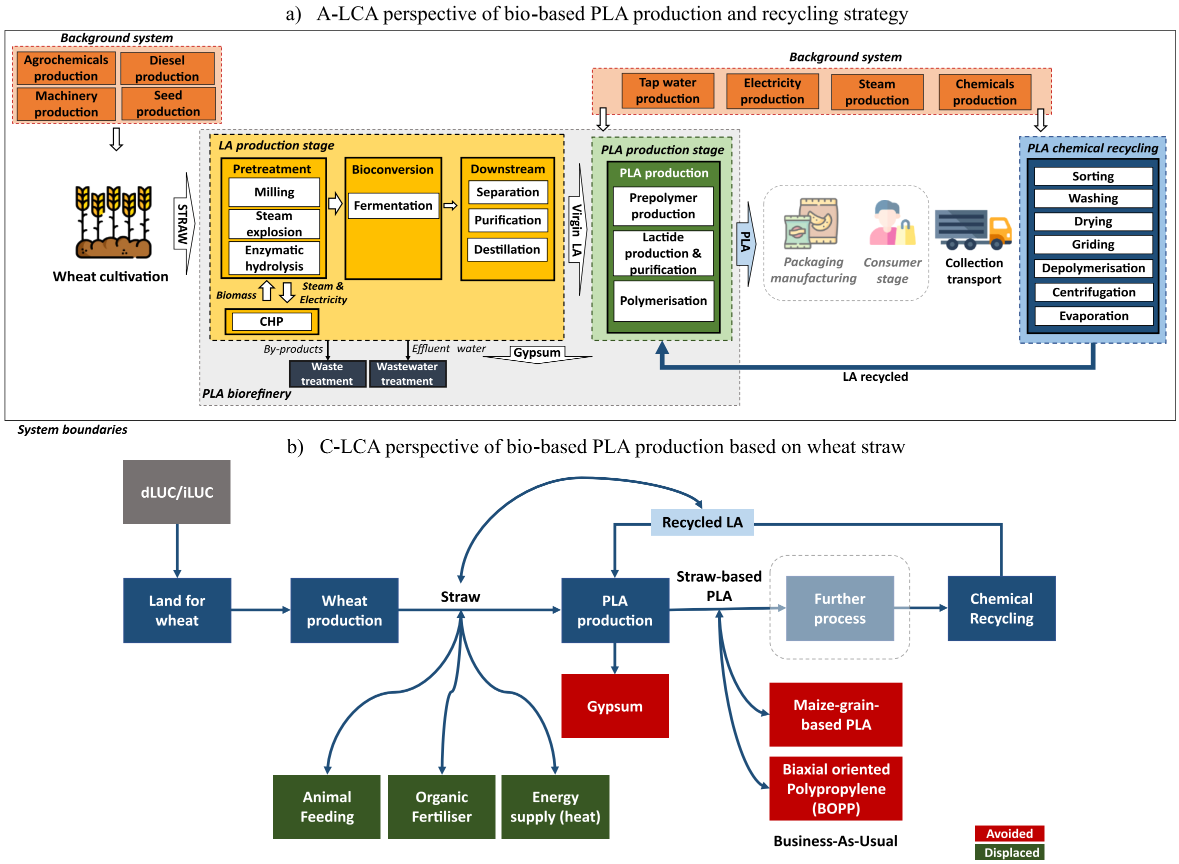

Fig. 1. System boundaries for Attributional and Consequential LCA approaches
(LA: lactic acid; PLA: polylactic acid; iLUC; indirect land use change; dLUC: direct land use change).

PLA was used as the functional unit (FU) to compare the straw-based PLA profile with previous studies in the literature. In the lactic acid production stage, calcium sulphate is also obtained (see Fig. 1a), which could be sold as gypsum (Ioannidou et al., 2022). An economic allocation was performed, since the main interest is the production of LA. The market prices considered were 8.6 USD·t^{-1} for gypsum (USGS, 2022), and 1500 USD·t^{-1} for lactic acid (Pharmacompass, 2022). Thus, allocation factors were 0.4% and 99.6% for gypsum and LA, respectively. Regarding end-of-life allocation, the recycled or cut-off content approach was considered; hence, recycled LA (from PLA waste) bears the loads from the time it is collected for recycling.

2.2. Process modelling

For the biorefinery and the recycling plant, an annual production capacity of 40,000 tons of PLA and recycled LA was assumed, respectively. Hence, the amount of LA that the biorefinery could obtain from the recycling plant is equivalent to 80% of its demand (as the biorefinery requires 50 kt y^{-1} of LA to produce 40 kt y^{-1} of PLA). In addition, a sensitivity analysis on the recycling levels was be performed. Furthermore, steam production was assumed to be provided by cogeneration systems to avoid the consumption of fossil resources in this bio-based production.

2.2.1. Wheat straw cultivation

Durum wheat (*triticum durum*) was grown on an area of approximately 0.25 ha in a monoculture regime in Apulia, Italy. The process begins in August with soil preparation and ends in June with grain harvesting. Wheat grain (13% moisture) and straw (10% moisture) with yields of 5.5 and 3.5 t·ha^{-1}, respectively, were obtained. The market prices were 0.29 €·kg^{-1} for the grain and 0.07 €·kg^{-1} for the straw.

2.2.2. Wheat straw pre-treatment stage

Straw composition (in dry matter) was 38.9% cellulose, 23.5% hemicellulose, 18% lignin, 4.5% protein, 14.5% extractives, 9.7% ash and 5.5% others (Carvalheiro et al., 2009). Straw is shredded to homogenize its size and then it undergoes a hydrothermal process for fractionation of the cellulose and hemicellulose components. The process is carried out under high pressure (19 bar) at 210 °C with a solid/steam ratio of 1:2 (Al-Zuhair et al., 2013). The solid and liquid fractions are separated by filtration. The solid stream goes to the enzymatic hydrolysis and the liquid fraction (hemicellulose-rich stream) is sent to the steam generation stage. Enzymatic hydrolysis is performed with 20 mg g^{-1} cellulose of Cellic® CTec3 cellulase (Novozyme, Denmark) at 50 °C for 72 h (Lopes et al., 2019). The solid lignin stream is recovered by filtration and passes to the steam generation stage. The glucose stream is sent to the lactic acid production section. The process modelling is presented in Fig. SM1 of the Supplementary Materials.

2.2.3. Lactic acid production

Process design for LA production is based on Qin et al. (2009) and Ioannidou et al. (2022). The assumptions taken for the process design were: LA concentration: 182 g L^{-1}; yield: 0.96 g g^{-1} and productivity: 2.88 g·$(L·h)^{-1}$ (Qin et al., 2009). Briefly, the bioconversion section was designed following Dheskali et al. (2017), and includes the formulation and sterilisation of fermentation media and starts with the mixing of process water with the carbon and nitrogen sources, salts and trace medium solution. The mixture is sterilised at 140 °C and then cooled to the fermentation temperature (37 °C). The downstream separation and purification (DSP) section is conducted in three stages and recovers L-lactic acid with high purity (99.4%) (Bapat et al., 2014). In the first stage, the bacterial biomass is separated from the fermentation broth by centrifugation. Then, to produce dilute lactic acid and solid calcium sulphate, calcium lactate is treated with 50% sulfuric acid at 30° for 1 h. Calcium sulphate is then separated from the product stream by centrifugation. Lactic acid is concentrated to about 50% (w/w) by evaporation, and the evaporated LA fraction is recycled. The second stage corresponds to esterification of the LA-rich liquid stream with methanol (99.6%) to obtain methyl lactate and water. The reactor product stream is heated to 105 °C. In the third stage, polymer-grade L-lactic acid is obtained by hydrolysis of methyl lactate in a reactive distillation column. Methanol and excess water are obtained as distillate. Methanol is recycled by distillation and sent to the second stage. The overall yield of the DSP section is 97.7%. The inventory data related to the mass and energy balances of lactic acid production for the A-LCA perspective is presented in **Table SM1** in the Supplementary Materials.

2.2.4. PLA production

The process design for PLA production is based on Gruber et al. (1993) and Ioannidou et al. (2022). The modelling of this process can be grouped into three subsections: prepolymer production, lactide production and PLA production. In the first subsection, LA is fed into the pre-polymer reactor, where it is condensed continuously by removing water at 120 °C for 1 h. Low molecular weight PLA (i.e., prepolymer) is formed when the LA undergoes a condensation reaction. Since the vapor stream contains vaporised LA and low molecular weight oligomers, a column is used to separate these elements from the water and return them to the process. In the second subsection, the prepolymer stream is introduced into the lactide reactor with tin octoate (catalyst), where the oligomers form lactide rings. With heat, the lactide is removed as vapor, while the liquid stream is recycled back to the reactor, as it contains unreacted oligomers. In addition to lactide, the vapor stream also contains unreacted lactic acid, lactic acid oligomers and water. Thus, the purification of lactide is carried out with two vacuum distillation columns. In the first, water is removed from the lactide stream, while the second column separates the residual lactic acid. The overhead products of the three distillation columns comprise a large amount of lactic acid, which is recycled back to the lactic acid recovery stage. In the final subsection, the purified lactide stream is mixed with tin octoate and fed into the polymerisation reactor, where high molecular weight PLA is produced. The resulting product stream contains a large amount of unreacted lactide, which is removed under vacuum in a devolatiliser and recycled back to the reactor. The refined PLA stream can then be granulated and stored (not included in this study). The inventory data of the polylactic production stage for the A-LCA perspective is presented in **Table SM2** in the Supplementary Materials.

2.2.5. PLA chemical recycling

The process modelling of the chemical recycling is based on Piemonte et al. (2013) and Aryan et al. (2021). The process modelling was simulated in Superpro designer® v11 software to scale up the production at industrial level. The transport distance of the collected PLA waste to the facility was assumed to be 25 km (Aryan et al., 2021). The composition of post-consumer PLA waste was obtained from Ginter (2019) and Aryan et al. (2021). Following them, post-consumer PLA waste was assumed to be disposable cutlery (e.g., food cups and plates) used at festivals and other recreational events, which is assimilated to municipal solid waste. Accordingly, for one tonne of waste, 988 kg of PLA (cups and plates), 4.68 kg of paper, 3.12 kg of plastic (polyethylene and BOPP from straws and packaging films, and polyethylene terephthalate from beverage cans and bottles), 1.92 kg of metal (crown caps) and 2.28 kg of other impurities (cigarette packets, leaves, soil, etc.) were obtained.

The recycling strategy begins with manual sorting, washing and shredding of PLA waste as a pre-treatment section. This is followed by the hydrolysis section with three process units: hydrolysis, separation and concentration. The hydrolysis reaction is performed with 20% PLA at 180 °C for 50 min (Piemonte et al., 2013). The separation unit corresponds to a centrifugation process to remove unreacted PLA, which is recycled back to the PLA depolymerisation reactor. An evaporator is then used to concentrate the lactic acid solution to 99% (Liang et al., 2013; Piemonte et al., 2013). The process modelling is presented in Fig. SM2, and the inventory data in **Table SM3,** both in the Supplementary Materials.

2.3. Consequential LCA modelling

In consequential LCA, the systems evaluated are composed by processes that are affected by a decision (mainly referring to changes in the demand for a product) (Schaubroeck et al., 2021). C-LCA also begins with the definition of the FU (1 kg PLA) and the definition of system boundaries (cradle-to-grave). The latter includes the activities that change in response to a change derived from the FU (see Fig. 1b). The objective is to determine which unit processes are affected by a change introduced through the functional unit and their causal relationships, assuming an elastic supply-demand relationship (Bello et al., 2022). The cause-effect events analysed through the C-LCA were: i) System boundaries were expanded to include the co-product (i.e., calcium sulphate) which is considered as avoided load from another market (i.e., fertilisation); ii) Animal feeding, organic fertilisation and energy generation are some of the main activities related to the use of wheat straw. Therefore, shifting to using wheat straw for producing PLA instead of upstream activities results in the need to offset these products; iii) straw-based PLA production will displace business-as-usual production methods in the market: PLA produced from maize grain, and polypropylene (BOPP), the fossil counterpart; iv) Recycling scheme will reduce the demand for the virgin resource (Consequential-LCA, 2017). In this case, since chemical recycling produces lactic acid, the demand reduction is associated with the amount of wheat straw needed to produce the required amount of this product.

In the case of displaced products, the forecasted PLA market shifts were studied through two perspectives. The first, the current perspective (CP), corresponds to the current production mix of total plastics in 2021, which was 90.2% from fossil resources, 8.3% from post-consumer recycling, and 1.5% from bio-based sources (Plastics Europe, 2022). Thus, it was assumed that of the virgin sources (i.e., 91.7%), 98.4% is from polypropylene and the remaining 1.6% is from 1G PLA. The second, the long-term perspective (LP), seeks the assumption of a future bio-based economy (i.e., no fossil-based plastics on the market). Hence, straw-based PLA would be expected to displace only 1G PLA.

The C-LCA modelling was performed through the four-step procedure proposed by Bjørn et al. (2018a):

- Step 1 - Identification of the type of changes (demand or supply): this study addresses the increase in wheat straw demand for the 2G PLA product.
- Step 2 - Identification of market constraints: the straw market is limited by the amount of wheat grain produced; therefore, the consequences of wheat straw demand will result in less straw available for other purposes. In other words, an increase in straw demand will reduce its availability in the market and cause other users to find a substitute, leading to an increase in demand for its equivalent marginal substitute.
- Step 3 - Product substitution: The overall procedure for identifying potential substitute products is described in Bjørn et al. (2018b). First, it is required to find potential straw applications and potentially affected users. In this regard, three straw use scenarios were considered: animal feed (AF), organic fertiliser (OF) and energy generation (EP). The first two are traditional practices and the last one could represent an interest in renewable energy generation (Giannoccaro et al., 2017). Next, it is necessary to identify the product that can function as a substitute for the potential application and determine whether its market is limited. In animal feed (AF scenario), wheat straw is used for its energy content, as the protein content is low (Heuzé et al., 2021). According to Fabbri et al. (2022),

barley is the potential displaced substitute in the animal feed market and its market is not limited. When the straw is left in the field (OF scenario), it can replace manure as potential organic substitute. Thus, the displacement of straw for PLA production will increase the demand for manure, which cannot be compensated by an increase in manure supply because its production depends on the demand for meat (i.e., it is a restricted market). Consequently, this supply deficit will lead to an increase in demand (and therefore supply) of synthetic fertilisers, which were modelled through the Ecoinvent® consequential database v3.8. In the case of energy production (EP scenario), straw can be used for heating generation, which is also modelled through the Ecoinvent consequential database v3.8.

- Step 4 - Identification of the affected production technology: Since the market for barley cultivation is not constrained, it is required to identify the production technology that is likely to be most affected by the increased demand for the substitute (which is being displaced using straw for PLA). Following the work of Fabbri et al. (2022), in a practical approach, it is not possible to choose between the least or most competitive production technology in the Ecoinvent® databases, since barley production processes are based on traditional agricultural practices and technologies. Thus, the technology affected was based on the information provided in the Ecoinvent® v3.8 database (i.e., the inventory process of barley production).

The consequential LCI representing the three traditional uses scenarios of straw and its substitutes are shown in **Tables SM4-SM11** of Supplementary Materials. Furthermore, the inventory data for both A-LCA and C-LCA approaches was modelling in the Simapro® v9.4 software, as well as the Ecoinvent® v3.8 database (Wernet et al., 2016) was used for obtaining the related background processes.

2.4. Land-use change emissions

Potential emissions from land use change (LUC) of bioplastics may limit their attractiveness to replace their petrochemical counterpart (Piemonte and Gironi, 2011). LUC emissions are classified as indirect (iLUC) and direct (dLUC). The first one occurs when land occupation for food (or feed) crops is converted into feedstock production for bioproducts; and the demand for the previous land use is maintained, making it necessary to compensate production capacity elsewhere. The second occurs when new agricultural land is implanted and the new feedstock (for bioproducts) modifies the previous land use, leading to possible changes in carbon stocks (Cherubini, 2010). In this manuscript, iLUC emissions were estimated following the biophysical model proposed by Tonini et al. (2016). According to this framework, there are two sources of additional demand for land and thus crop production: land expansion (i.e., deforestation) and intensification of currently used land. Based on Tonini et al. (2016), the proportion of sources for crop production change was 25% expansion of cultivated area and 75% intensification (increased yields). In the expansion approach, the model considers geographic location and biomass affected, as well as changes in carbon (C) and nitrogen (N) flows. In the case of intensification, it considers the increased use of N, phosphorus (P) and potassium (K) fertilisers, as well as field emissions related to their application. For more details, please see Tonini et al. (2016). Following Bishop et al. (2021b), the arable land demanded by wheat straw to produce PLA was estimated at 12.6 $m^2a \cdot kg^{-1}$ PLA based on the Ecoinvent® v3.8 consequential database. Moreover, a straw yield of 0.8 kg kg^{-1} wheat grain was considered (Weiser et al., 2014). Background emissions from fertiliser production were also modelled using the same database. See **Table SM4** for iLUC inventory emissions. Regarding the dLUC, emissions were not accounted for because the Apulia region is the largest producer of durum wheat in Italy (Bux et al., 2022). Therefore, it was assumed that there was no change in land use in the last 20 years.

2.5. Life cycle impact assessment

To estimate the potential environmental burdens of PLA production, two Life Cycle Impact Assessment (LCIA) methods were considered for the midpoint impact and endpoint damage categories (see Fig. 2): ReCiPe 2016 Midpoint (H) v1.07/World (2010) to obtain the characterisation factors, and ReCiPe 2016 Endpoint (H) v1.07/World (2010) H/A to obtain single score values (Huijbregts et al., 2017). The single score was used to compare environmental damage between PLA production with 100% virgin straw and with LA obtained from the recycling strategy. For both LCIA methods, all impact and damage categories were analysed. The selection of the ReCiPe method was motivated by the fact that it provides characterization factors representative of the global scale, and it is one of the most widely used because it is frequently updated (Borghesi et al., 2022).

2.6. Sensitivity and uncertainty analysis in the A-LCA approach

Three potential variations in the results were considered as sensitivity analyses:

- The first one is related to a variation in the cellulose content in the wheat straw as: 28%–39% (Camara-Salim et al., 2021). Consequently, it was considered the feedstock composition of Nabarlatz et al. (2007): cellulose 28.4%, hemicellulose 22.5%, and lignin 15.9%.
- The second one focused on the price of wheat straw, as its market is restricted, a higher demand may increase the value of this feedstock. Considering the baseline price (i.e., 0.07 €$\cdot kg^{-1}$), an increase of two (0.14 €$\cdot kg^{-1}$), three (0.21 €$\cdot kg^{-1}$) and five (0.42 €$\cdot kg^{-1}$) times was considered, maintaining the same price of the grain. Thus, the allocation factors for the straw grow to 25.3%, 33.6%, and 45.8%.
- Thirdly, a distance value of 25 km was considered in the baseline for collecting the PLA waste in the transport stage (Aryan et al., 2021). Accordingly, this stage may represent a source of uncertainty in the environmental burdens, thus, the influence of this stage on the environmental profile was addressed increasing by twice and three times the distance considered.

The uncertainty analysis was performed following the work of Wang et al. (2023), in which the effect of the uncertainty of the crop in the bioproduct profile using the Montecarlo method. Due to the lack of data in this stage, the values of the pedigree matrix and the standard deviation of each flow (e.g., fertiliser, pesticides) were obtained from the ecoinvent® v3.8 database.

3. Results and discussion

3.1. Material and energy flows analysis

Regarding the material flows analysis is possible to indicate that about 4.54 kg of wheat straw are required to produce 1 kg of PLA. In addition, water consumption reached the greatest consumption in the pre-treatment (74%) and bioconversion stages (15%). Concerning the energy flows, the total electricity consumption was 1.16 kWh per kg of PLA, which was mainly spent in the bioconversion (41%) and pre-treatment (37%) stages. The low-pressure steam comprised about two times the demand of the high-pressure one. The low-pressure steam was more consumed in the DSP stage, specifically, in the distillation process (49% of the total). On the other hand, the high-pressure steam was mostly spent in the PLA polymerisation stage, being the lactide production the process that stood out with about 65% of the total.

Fig. 2. Impact and damage categories analysed.

3.2. Attributional LCA results of 2G PLA production

3.2.1. Midpoint impact categories

The environmental profile of straw-based PLA is presented in Table 1. The prepolymer production was the stage that accounted for the highest impacts contribution (see Fig. 3a) encompassing about 75% in all categories due to LA production (see Fig. 3b). The contribution of lactide production stage with approximately 15% in the LU category is caused by the background process of wood chip demand for steam production. The impacts associated with virgin LA production were caused by the straw pre-treatment process to obtain fermentable sugars and the DSP processes (see Fig. 3c). In the pre-treatment stage, the impacts related to wheat straw cultivation are the main hotspot, while in the DSP stage the burdens are related to the first of the three stages of pure L-lactic acid recovery. In addition, the bioconversion process has similar contribution to the DSP stage in FE and FRS categories, and it is the second most relevant in GW (30%), because of the electricity demand.

Regarding other A-LCA studies from the literature, Ioannidou et al. (2022) estimated the potential environmental burdens of PLA from corn glucose syrup, corn stover and sugar beet pulp (SBP). They obtained a GW profile for the PLA production of 0.95, 1.04 and 2.25 kg CO_2eq per kg of product from glucose syrup, corn stover and SBP, respectively. The lowest GW of glucose syrup was due to the consideration of biogenic CO_2 of corn cultivation (−1.28 kg CO_2eq·kg^{-1} PLA). From the Ecoinvent® database v3.8 (Wernet et al., 2016), it was possible to compare the GW profile of PLA production derived from maize-grain (by NatureWorks) with impacts of 2.83 and 3.05 kg CO_2eq per kg of product, depending on the selected inventory process: polylactide granulate {GLO}| production and polylactide granulate at plant/GLO U, respectively. Furthermore, the fossil counterpart biaxial oriented polypropylene (BOPP) reaches an impact of 2 kg CO_2eq·kg^{-1} BOPP according to PlasticsEurope (Ioannidou et al., 2022). From the above-mentioned, the result related to this impact category was lower in this manuscript. However, it is relevant to indicate that considering a fossil source such as natural gas for the steam production, the GW profile of straw-based PLA can rise to 2.27 kg CO_2eq per kg of product, which is still better compared to current the 1G feedstock (i.e., maize). This represents a key reason for supporting that all background processes avoid fossil fuel consumption in the manufacture of bio-based products.

In addition, the research of Lee et al. (2021) estimated the environmental impacts of the LA production from wet waste feedstocks (e.g., wastewater sludge and food waste), finding per kg of product a range value from −4.2 to −1.4 kg CO_2eq, which is far from the 1.06 kg CO_2eq obtained here. Then, Kim et al. (2022b) extended the previous work to estimate the life-cycle burdens of waste-to-PLA pathways, reaching a GW profile of −1.5, −3.4, and −3.6 kg CO_2eq per kg for wastewater sludge-, food waste-, and swine manure-derived PLA, respectively. One of the differences with the abovementioned works corresponds to the use of the GREET model in the impact assessment stage, but most importantly, the consideration of avoided emissions from business-as-usual scenarios and displaced counterpart.

Table 1
Attributional environmental profile of 1 kg of PLA.

Impact category	Acronym	Unit	PLA product
Global warming	GW	kg CO_2 eq	1.38
Stratospheric ozone depletion	SOD	mg CFC_{11}eq	7.50
Ionising radiation	IR	kBq Co-60 eq	0.30
Ozone formation. human health	OF. HH	g NOx eq	4.23
Fine particulate matter formation	PM	g $PM_{2.5}$ eq	5.22
Ozone formation. terrestrial ecosystems	OF. TE	g NOx eq	4.31
Terrestrial acidification	TA	g SO_2 eq	17.40
Freshwater eutrophication	FE	g P eq	0.86
Marine eutrophication	ME	g N eq	1.71
Terrestrial ecotoxicity	TET	kg 1.4-DCB	9.29
Freshwater ecotoxicity	FET	kg 1.4-DCB	0.18
Marine ecotoxicity	MET	kg 1.4-DCB	0.25
Human carcinogenic toxicity	HCT	g 1.4-DCB	66.72
Human non-carcinogenic toxicity	HNCT	kg 1.4-DCB	6.53
Land use	LU	m^2a crop eq	0.39
Mineral resource scarcity	MRS	kg Cu eq	0.01
Fossil resource scarcity	FRS	kg oil eq	0.40
Water consumption	WC	m^3	0.13

3.2.2. Endpoint environmental results

In the endpoint perspective (see Fig. 4), PLA production from wheat straw reached a total value of 114 mPt. As in the midpoint categories, the prepolymer production step contributed the most to the single score (see Fig. 4a), approximately 98% of the total, due to the LA production. The virgin lactic acid production stage obtained a value of 88 mPt and presented a balanced contribution to the total score between the pre-treatment and DSP stages, with 42% and 44%, respectively (see

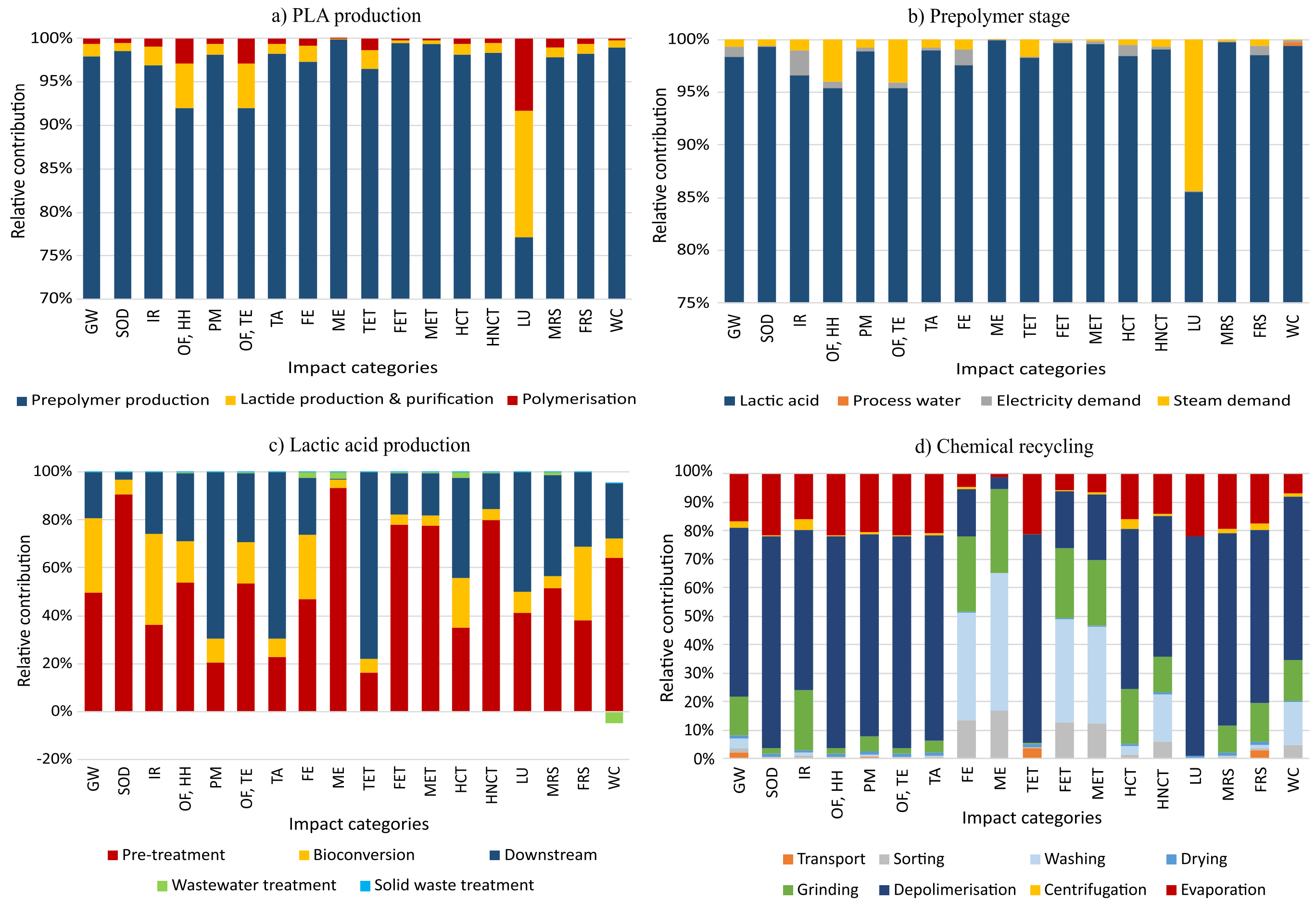

Fig. 3. Distribution of contributions to the environmental profile per areas involved in the whole production system. (GW: Global warming: SOD: Stratospheric ozone depletion; IR: Ionising radiation; OF, HH: Ozone formation, human health; PM: Fine particulate matter formation; OF, TE: Ozone formation, terrestrial ecosystems; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication: TET: Terrestrial ecotoxicity; FET: Freshwater ecotoxicity; MET: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption.)

Fig. 4b). Human health was the category with the highest observed damage in the LA product system, due to the pre-treatment and downstream processes. In the former, wheat straw cultivation and ash treatment, and sulfuric acid demand in the latter, were the main factors responsible.

3.2.3. Integration of recycled LA in the 2G PLA production

The objective of integrating an EoL stage of PLA waste (in this case, chemical recycling) into the production scheme was addressed to determine the potential benefits of this strategy. Regarding the environmental performance of the chemical recycling stage, the depolymerisation process was the main hotspot (see Fig. 3d), standing out in 14 out of 18 categories. In the remaining four categories (i.e., FE, ME, FET, and MET), the disposal of other collected plastics waste at sanitary landfill was the main responsible. In addition, steam demand was the critical factor in this recycling process, so the source of steam generation plays a critical role in the environmental viability of this EoL. Other sources such as natural gas can increase, for instance, the GW profile from 0.12 to about 1.6 kg CO_2eq per kg of recycled LA. Although the cogeneration process represents a suitable source to reduce GHG emissions, land use related impacts are the main concern. On the other hand, the EoL strategy presented a total single score of 10.9 mPt, with depolymerisation and evaporation being the most critical stages with about 63% and 18% of the total score, respectively (see Fig. 4c), due to steam demand.

Fig. 5a shows the variation in the PLA profile using a range of 0%–80% of recycled LA. The results of the environmental profile of 2G PLA ranged from 1.38 to 0.44 kg CO_2eq in the GW category, a reduction of almost 70%. A remarkable decrease was obtained in WC category with 76%, from 0.13 to 0.03 m^3. However, the only increase in environmental burdens (55%) was identified in the LU category, due to the energy demand supplied by the cogeneration system, which is based on the wood resource. The single score was used to compare the potential environmental damages between PLA production with 100% virgin straw and the integration of the recycling strategy. Single score results (see Fig. 5b) showed a reduction of the potential damages of 2G-PLA from 113 to 37 mPt (i.e., about 68%) in the total score with the highest recycled LA capacity. Human health and resource quality were the damage categories that achieved the largest decrease. In the case of human health, it decreased from 109 to 34 mPt (69%), while resource quality decreased from 0.8 to 0.2 (70%). Ecosystem category reached a decrease of about 36%, from 3.8 to 2.4 mPt. The reason behind these reductions could be explained by the differences between the single score of LA obtained from the valorisation of virgin straw and recycling routes. In human health category, the score of LA from virgin straw was 87.8 mPt and 10.9 mPt for the chemical recycling. In resources category, the virgin LA score was ten-times higher than the recycled one (0.61 and 0.06 mPt). Whereas in the ecosystem category the difference was lower, where a value of 3 mPt and 1.3 mPt was obtained for LA from virgin straw and recycling sources, respectively. In this category, the damages

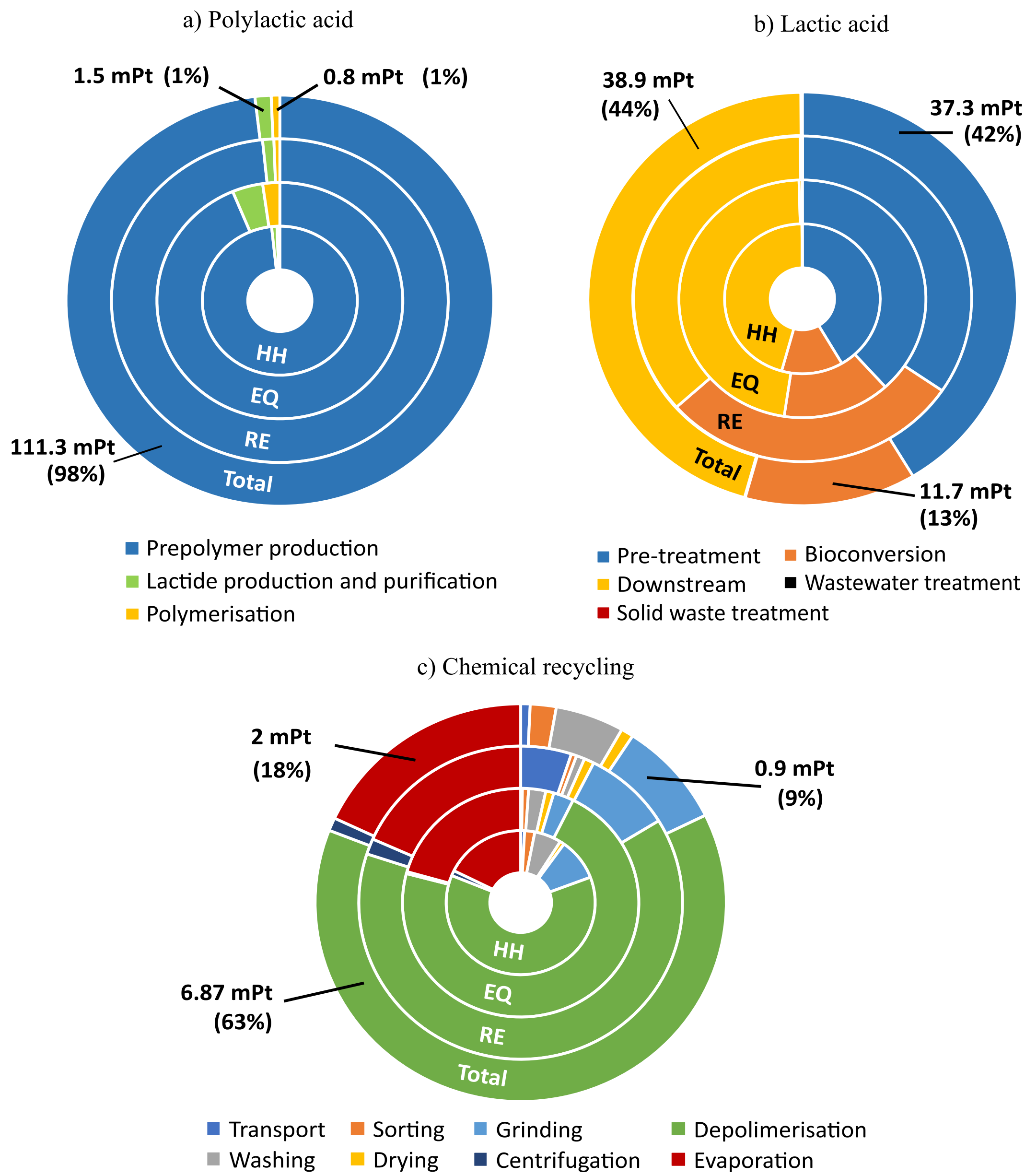

Fig. 4. Endpoint single scores for polylactic acid production and end of life stages. (In this figure HH: Human health; EQ: Ecosystem quality; RS: Resource scarcity).

of the virgin LA production were motivated by the pre-treatment section (1.17 mPt) because of straw production (0.6 mPt) and the downstream processes (1.11 mPt) which are caused by the sulfuric acid (67%) mainly. On the contrary, in the case of the recycling strategy, the damage mainly was observed in the depolymerisation section (0.96 mPt) due to steam demand (56 kPt).

3.3. Sensitivity and uncertainty analysis in the A-LCA approach

Fig. 6 shows the changes in the environmental profile of the straw-based PLA considering the selected parameters. In the first case (see Fig. 6a), a lower cellulose content led to an increase in the burdens due to the higher quantity of wheat straw required to produce 1 kg of polymer. In the GW category, the impacts grow 9% reaching about 1.51 kg CO2eq per kg of PLA. A variation between 5 and 7% in FET, MET, and HNCT categories was identified, which depends mainly on the emissions related to the ash disposal treatment. This result could be explained by the slight difference in the amount of ash treated: 0.31 and 0.28 kg per kg of LA in the baseline and the sensitivity scenario, respectively. Furthermore, a reduction of about 21% in the LU category could be explained as more residual biomass was available to be used for steam generation.

The second analysis related to the price of the straw showed, for instance, that a rise of 2, 3 and 5 times the price of the baseline could represent a grow of 20%, 35%, and 58% in the GW category (see Fig. 6b). The higher variations were observed in SOD, ME, and MRS, where the burdens related to the agricultural stage reached a higher relevance. Regarding the variation of the distance for collecting the PLA waste (see Fig. 6c), it was identified that the greatest changes occur in GW, TET, and FRS categories. A four-times increase (i.e., 100 km) led to a rise of 7% in GW, 12% in TET, and 9% in FRS in the LA recycled. Moreover, a ten-times growth (i.e., 250 km) would imply an increase of

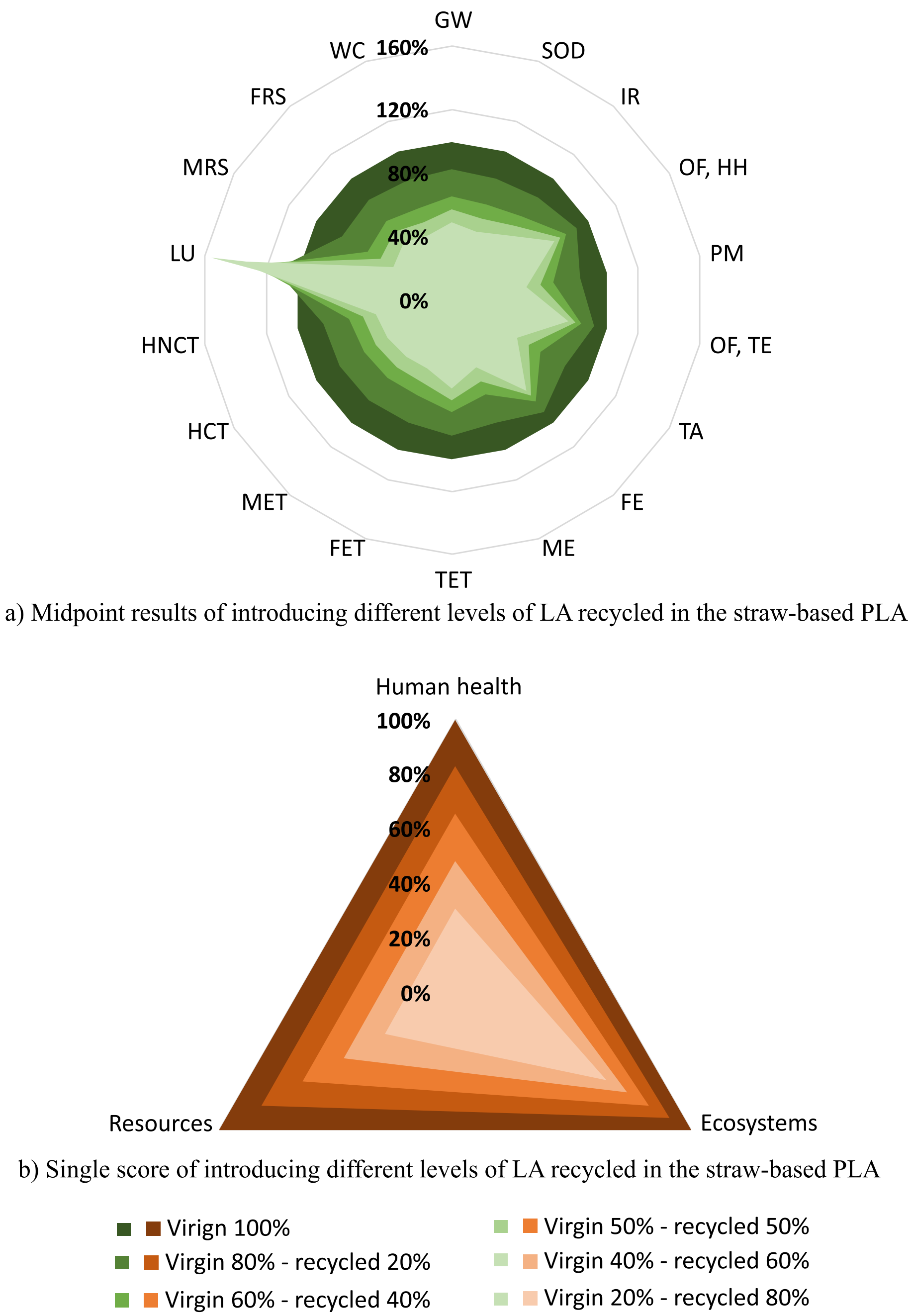

Fig. 5. Comparison among environmental profiles of PLA with different recycling levels (GW: Global warming; SOD: Stratospheric ozone depletion; IR: Ionising radiation; OF, HH: Ozone formation, human health; PM: Fine particulate matter formation; OF, TE: Ozone formation, terrestrial ecosystems; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; TET: Terrestrial ecotoxicity; FET: Freshwater ecotoxicity: MET: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption.).

21%, 35%, and 28%, in GW, TET, and FRS, respectively. Thus, with the higher distance, the PLA profile made with 80% recycled LA could only increase by about 5.9% in the GW profile.

Regarding the uncertainty analysis, to obtain the distribution of the burdens, the LCA calculation process was repeated 10,000 times using the Montecarlo method, and the results obtained were presented in **Table SM12** in the supplementary materials. In this regard, the standard deviation, for instance, in the GW profile was 0.07 kg CO_2eq per kg of PLA with a full demand of virgin LA, which demonstrated that including the uncertainty of the crop production process affected the environmental profile of the straw-PLA as could be expected.

3.4. Consequential LCA results

Table 2 shows the environmental implications according to the two perspectives CL and LP evaluated for the three substitutes scenarios considered in the straw-based PLA production. Accordingly, six main findings are identified and discussed. First, 2G PLA production can lead to both benefits (i.e., negative impact results) and burdens (positive impact results), depending on the substitution hypothesis and the impact category analysed. Second, in both perspectives, the reduction of straw availability for energy purposes (in this case for heating production) results in the highest environmental burdens of the substitution scenarios evaluated. Third, the substitution of the fossil counterpart (i.e., polypropylene) leads to higher burdens than the substitution of a 1G PLA, because the avoided impacts with maize-based PLA were higher than the impacts avoided with PP (see Fig. 7). Fourth, most benefits were observed when straw was used as animal feed (AF scenario) in five categories such as FE, FET, LU, FRS, and WC in the LP perspective. In this regard, among the three traditional uses of straw evaluated and with the only exception of the IR category, the displacement of straw when it was used for animal feeding was the preferred alternative because the

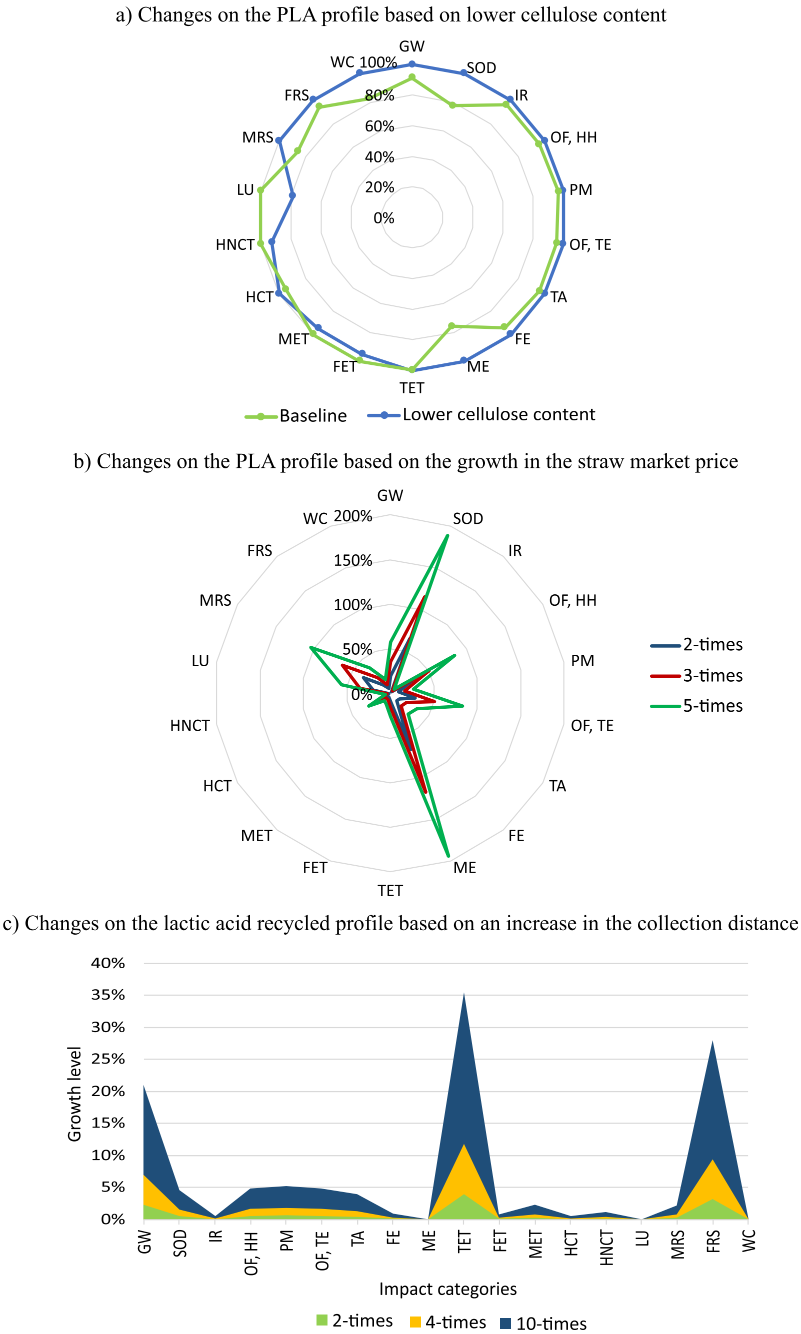

Fig. 6. Sensitivity analysis in the attributional LCA approach (GW: Global warming, SOD: Stratospheric ozone depletion; IR: Ionising radiation; OF, HH: Ozone formation, human health; PM: Fine particulate matter formation; OF, TE: Ozone formation, terrestrial ecosystems; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; TET: Terrestrial ecotoxicity; FET: Freshwater ecotoxicity; MET: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity: LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption.).

burdens of its substitute product are compensated by the avoided (fossil and 1G) polymer production. Fifth, in all categories both perspectives have the same order of preference when comparing scenarios. Sixth, iLUC emissions were the main responsible of the burdens in all scenarios and in both perspectives.

Focusing on the GW category, the EP scenario gets the worst impact value in both perspectives. The reason is that above half (53–57%) of the impacts would be driven by energy production from sources such as hard coal, lignite, and wood chips (see Fig. 7c). Furthermore, the OF scenario achieved the highest impacts in TET and MRS categories of the three scenarios in CP and LP perspectives. Inorganic fertiliser production represents the main contributor in most of the categories evaluated in this scenario (see Fig. 7b). The AF scenario achieved the lowest impact scores of the three scenarios in both perspectives, where barley grain production burdens were relevant in the LU category with about 45% in the CP perspective, but not significant in the LP perspective in all categories (see Fig. 7a). As for the identified benefits, the AF alternative would achieve them in the FRS category for both perspectives and the OF scenario in the CP approach. Also, both substitution scenarios could reach benefits in LU and WC categories but only in the LP perspective. The benefits related to the avoidance of gypsum products were not significant.

Regarding the iLUC emissions, they are a significant contributor in the environmental implications of the potential implementation of the straw-based PLA production. They increase global warming impacts by 6.69 kg CO_2eq per functional unit. In the AF scenario, they are the main responsible of burdens in most of the categories, where land expansion was the main contributor in GW (see Fig. 7a). Fertilisers production for intensive land use was the main contributor in TET, MET, HCT, HNCT, and MRS categories, whereas their direct emissions highlighted in PM,

Table 2
Consequential LCA results of the scenarios under study. Environmental savings are denoted by negative values. whereas positive values represent burden increases.

Impact category	Unit	CP scenario			LP scenario		
		AF	OF	EP	AF	OF	EP
GW	kg CO_2 eq	4.80	8.92	13.83	3.01	7.13	10.41
SOD	mg CFC11 eq	72.87	107.75	73.19	61.94	96.82	62.14
IR	kBq Co-60 eq	−0.08	−0.15	−0.42	0.14	0.07	−0.14
OF, HH	g NOx eq	9.37	16.16	32.74	6.80	13.58	25.94
PM	g PM2.5 eq	2.76	7.54	16.30	1.64	6.43	12.74
OF, TE	g NOx eq	9.13	16.13	32.54	6.43	13.42	25.60
TA	g SO2 eq	14.23	27.64	64.83	8.91	22.32	50.34
FE	g P eq	0.29	1.26	15.73	−0.31	0.66	12.35
ME	g N eq	2.84	2.86	3.65	1.59	1.61	2.22
TET	kg 1,4-DCB	2.11	8.94	2.73	0.90	7.73	1.40
FET	g 1,4-DCB	7.61	36.41	403.98	−4.40	24.40	320.45
MET	g 1,4-DCB	10.58	51.65	556.69	3.59	44.67	451.14
HCT	kg 1,4-DCB	−0.01	0.03	0.81	0.01	0.05	0.68
HNCT	kg 1,4-DCB	0.43	1.64	18.04	0.21	1.42	14.63
LU	m2a crop eq	0.10	0.15	2.97	−0.27	−0.21	2.08
MRS	kg Cu eq	0.02	0.06	0.02	0.01	0.05	0.01
FRS	kg oil eq	−1.13	−0.16	0.82	−0.76	0.21	0.84
WC	m^3	0.03	0.08	0.38	−0.07	−0.02	0.22

Acronyms: AF: Animal feed; OF: Organic fertiliser; EP: Energy production; CP: Current perspective; LP: Long-term perspective; GW: Global warming; SOD: Stratospheric ozone depletion; IR: Ionising radiation; OF, HH: Ozone formation, human health; PM: Fine particulate matter formation; OF, TE: Ozone formation, terrestrial ecosystems; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; TET: Terrestrial ecotoxicity; FET: Freshwater ecotoxicity; MET: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption.

TA, and ME. In the case of the OF scenario, iLUC emissions were not so relevant (as in EP scenario), since substitutes products were the most contributor, i.e., inorganic fertiliser and heat production. However, they highlighted in GW, SOD, TA, and ME categories (see Fig. 7b), because of direct emissions related to the intensification of land use. In the EP scenario, iLUC emissions were relevant in ME, TET, and MRS categories, mainly, because of fertilisers production for the intensive land use.

Finally, it is relevant to consider that higher iLUC emissions could be estimated when a low efficiency resource of the feedstock is reached in the production of the bio-product. For instance, it was estimated that 4.54 kg of straw is needed to produce 1 kg of PLA, but a lower cellulose content (as mentioned in the sensitivity analysis section) could increase the straw demand to 6.22 kg per kg of PLA, and consequently, rise the iLUC emissions by 37% of CO_2eq, mainly due to the land expansion component. In this way, both the lignocellulose content of the feedstock and the high conversion rate into fermentable sugars will be crucial in the environmental effects of this system.

When recycling was considered in the environmental consequences, assuming the full capacity of the recycling plant (i.e., 80% of the demand of LA), the CP perspective (see Fig. 8a) showed a significant reduction of the impacts in all categories for the three substitutes scenarios of the straw use. For example, the GW results per kg of PLA were −0.52 kg CO_2eq in AF scenario, 0.31 and 0.96 kg CO_2eq for OF and EP scenarios, respectively. Again, the AF scenario obtained the highest number of categories with environmental benefits. Additionally, when benefits were obtained with 100% virgin straw, they were increased with recycling, for example in HCT and FRS categories. In the LP perspective (see Fig. 8b), a great number of categories presented benefits, specifically, in the AF scenario. Integrating a recycling plant into the straw-based PLA biorefinery leads to a lower demand for virgin feedstock, which implies less requirement of land conversion for feedstock cultivation and its related emissions (i.e., iLUC emissions); as well as avoid the increase demand of substitute products for fertilisation, feeding or energy generation activities.

3.5. *Potential limitations of promoting straw-based PLA and future research*

To promote bio-based systems, some limitations should be addressed. The introduction of bioplastics in the market is limited by their high cost (Bishop et al., 2021b). For instance, the market price of PLA (1.91–2.64 USD·kg^{-1}) is higher than its fossil-counterpart BOPP (1.08–2.00 USD·kg^{-1}) (Ioannidou et al., 2022). Recently, the techno-economic analysis by Ioannidou et al. (2022) of PLA production from glucose syrup, SBP, and corn stover reported production capacities to obtain economies of scale. In this way, the life-cycle costs of the straw-based PLA should be conducted to explore its economic sustainability as future research, as well as to determine the economic implications of integrating a recycling plant in the bio-PLA production or evaluating different end-of-life alternatives.

Another obstacle in the commercial feasibility of straw-PLA is the need for contracts with farmers to guarantee the feedstock supply (Glithero et al., 2013). According to Giannoccaro et al. (2017), in the Apulia region, Italy, straw is considered a valuable resource, and its current use offers different benefits to farmers: *i*) traditional burning generates benefits in pest and weed reduction for the next cultivation season; *ii*) income from sales to well-established markets; and *iii*) incorporation into the soil, in line with Good Agricultural and Environmental Conditions or in order to obtain a state subsidy according to the Agro-Environmental Schemes. These authors also established that since income from straw are less than 10% of total income from grain production, land occupation will not be affected in the short term by an increase in the demand; and the willingness of farmers to sell will be influenced by price. In this regard, Giannoccaro et al. (2017) identified that 12 €·ha^{-1} is the most common price for straw sold in-swath, and that the willingness to accept selling straw in-swath on the feedstock market ranges from 2 to 22 €·ha^{-1}. Thus, stakeholders should aware that straw value does not depend on production costs, but rather on the availability of the resource; while policy-makers could coordinate their efforts to align policies to reduce market distortions that subsidies can cause in increasing straw prices.

The main limitation of this research was focused on the uncertainty approach due to the lack of data in the stage related to the cultivation of the crop, which has been addressed with data from the ecoinvent database using a generic dataset related to this process. In addition, future research could be also focused on the social implications of this product system based on the social LCA approach, to identify the stakeholders affected or benefiting from this circular model, and the social implications of substitution scenarios. Since traditional activities such as animal feed, organic fertilizers and heat generation were studied

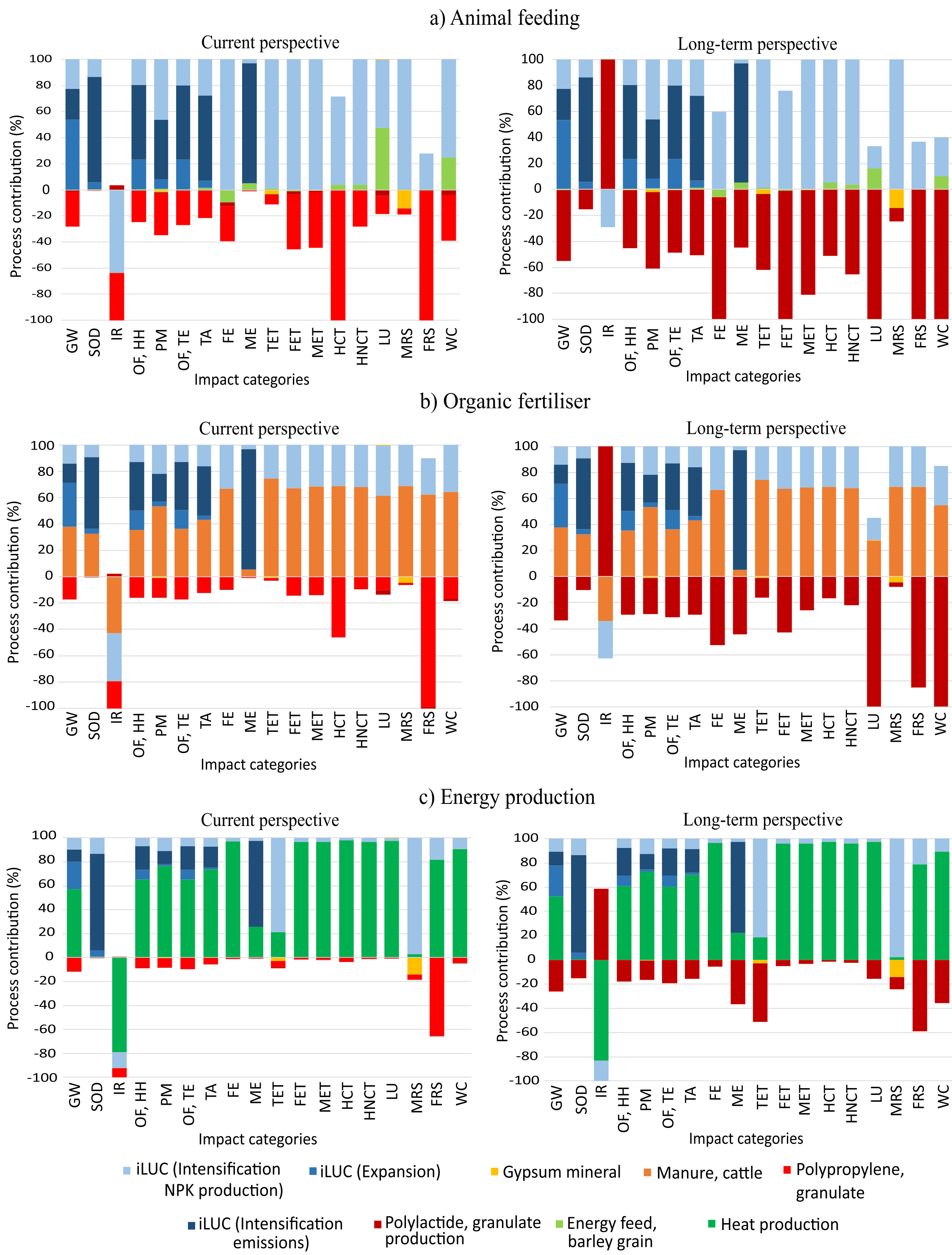

Fig. 7. Contribution of life cycle processes in the consequential LCA approach (GW: Global warming: SOD: Stratospheric ozone depletion; IR: Ionising radiation; OF, HH: Ozone formation, human health; PM: Fine particulate matter formation; OF, TE: Ozone formation, terrestrial ecosystems: TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; TET: Terrestrial ecotoxicity; FET: Freshwater ecotoxicity; MET: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity: LU: Land use; MRS: Mineral resource scarcity, FRS: Fossil resource scarcity: WC: Water consumption.).

as product scenarios displaced from wheat straw, it could be interesting to analyse other second-generation energy vectors and biomaterials as substitute products for the resulting bioeconomy models.

4. Conclusions

Biorefinery platform proposed in the literature are focused on the attributional environmental impacts of the bioproduct. However, the adoption of a comprehensive assessment, considering a consequential

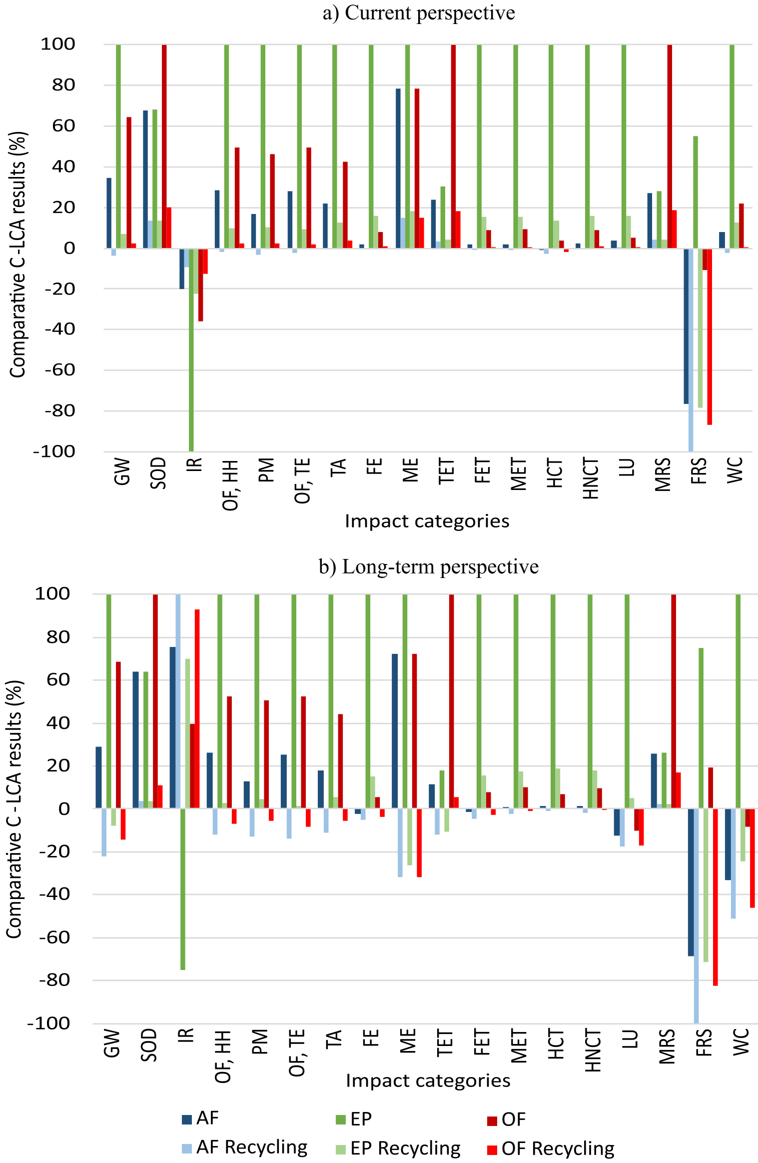

Fig. 8. Comparative results of consequential LCA approaches including recycling plant (AF: Animal feeding; EP: Energy production; OF: Organic fertiliser.).

perspective, allows the identification of potential effects related to the displacement of substitute products, both petrochemicals and (first generation) bioproducts, motivated by a new valorisation pathway.

In the A-LCA perspective, the main hotspot of straw-based PLA was related to LA production, which is due to the pre-treatment of straw and the downstream separation and purification stage. On the other hand, the C-LCA results showed that the shift from the traditional use of wheat straw (i.e., fertilisation, feed, or energy purposes) towards PLA production may represent burdens related to an increasing demand for substitute products for these activities, as well as the demand for land conversion and its related emissions (i.e., iLUC emissions). In this sense, the wide range of wheat straw utilisation possibilities will determine the environmental implications (positive or negative) of this 2G PLA. In addition, integrating a recycling plant into the PLA biorefinery greatly influences its environmental viability, reducing both the attributable impacts and the environmental consequences.

CRediT authorship contribution statement

Ricardo Rebolledo-Leiva: Conceptualization, Investigation, Methodology, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Dimitrios Ladakis:** Supervision, Writing – review & editing, Validation. **Sofia-Maria Ioannidou:** Software, Writing – review & editing. **Apostolis Koutinas:** Supervision, Writing – review & editing, Validation. **Maria Teresa Moreira:** Supervision, Writing – review & editing, Visualization. **Sara González-García:** Supervision, Writing – review & editing, Visualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138354.

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