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Research Article

Life Cycle Assessment of a Circular Economy Process for Tray Production via Water-Based Upcycling of Vegetable Waste

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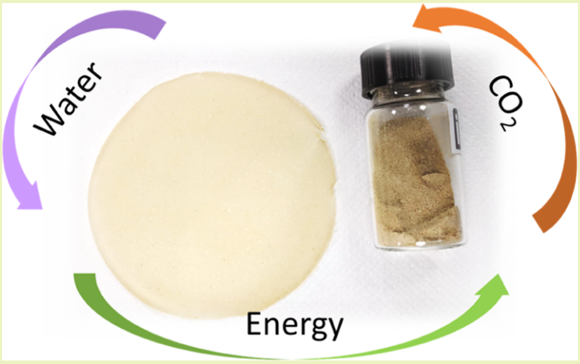

ABSTRACT: With one-third of food being wasted at the various steps of the value chain, there is a large amount of biomass constantly being discarded, also wasting the resources consumed for its production. Several strategies have been proposed to use this biomass as a source of raw materials for the production of plastic alternatives, but the environmental impact parameters have rarely been estimated to understand if the proposed process provides an overall benefit. The purpose of this paper is to analyze, through an experimental laboratory campaign, the production process of a vegetable biocomposite material obtained by valorization of biomass from two sources: unsold vegetables from a wholesale market and carrot pomace obtained as a byproduct of juicing. The obtained biocomposite films were thermoformed into trays to replace the traditional plastic food containers made principally with PET. Different scenarios for the lab-scale production of trays were evaluated by testing two water-based processing methods for the two types of biomass used. In order to understand which of the four scenarios was the least impactful, the global warming potential, the cumulative energy demand, and the water scarcity index were used as indicators. Among the different lab-scale processing scenarios for the upscaling of vegetable waste, the least impactful was starting from the unsold/discarded vegetables collected at the wholesale market that were processed via water-based hydrolysis catalyzed by formic acid. Impact parameters were comparable or better than two traditional polymers (PET and HDPE) and two biopolymers (PLA and biopolymer from starch), showing that this process has excellent potential, from an environmental point of view, of substituting plastic packaging.

KEYWORDS: *biocomposite materials, food packaging, water−energy−food nexus, life cycle approach, circular economy*

■ INTRODUCTION

While the linear economy has played an essential role in the development of economy and industry, it generated a significant stress in the environment due to the overuse of natural resources and improper waste disposal.[1] In particular, the final disposal of solid waste has become one of society's greatest challenges,[2] with the management of plastic waste being particularly problematic. The European Commission recently adopted a strategy on single-use plastics as part of the transition to a more circular economy, which aims at protecting the environment from plastic pollution[3] and consequently improving the public health of citizens. Under the new plan, plastic packaging on the EU market must be 100% recycled by 2030, the use of single-use plastic bags will be reduced, and the intentional use of microplastics will be limited (Italy, with its 2018 Budget Law, has banned the marketing of cosmetic rinse-off products with exfoliating or cleansing action containing microplastics from January 1, 2020).[4] Concerns about conventional petroleum-based plastics also arise from the finite nature of fossil-based resources, supply restrictions from some producing countries, price volatility, increased costs of disposal, energy costs of separation and recycling, and finally plastic accumulation in the environment, with its associated hazards with wildlife on land and in the oceans.[5,6] Bioplastics were developed to mitigate at least some of these problems. They are defined as materials that are either produced from renewable sources, or that are biodegradable, or that have both characteristics.[7] Currently, only 1% of plastics commercialized annually are bioplastics,[8] a market that is expected to grow. However, some drawbacks of current bioplastics, such as the elevated temperature required for PLA's compostability, caused EU regulators to associate them with oil-based plastics, limiting their adoption for single-use objects.[9] Stronger concerns on the End of Life of plastic waste, together with EU regulations

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aimed at pushing toward a higher percentage of plastic recycling, is creating a scenario in which landfilling costs continuously increase, spurring the need for a new strategy to upcycle waste streams into useful products. A circular economy approach is seen as a new and viable solution for this problem:[10] biomass unused or discarded from the food value chain could become a renewable source of raw materials that, if properly processed, could substitute plastics. For this approach to succeed, new technologies and engineering methods are required for the conversion of biomass into new materials with satisfactory performance. If properly engineered, the developed bio-based materials should preserve the good biodegradability profile of the original natural materials, helping reduce the pollution generated by non-biodegradable or poorly biodegradable plastics.[11,12] Although circular economy is appealing, when new processes are proposed, it is important to make sure that the new circular strategy will actually reduce the negative environmental and social impacts of products. This is an often overlooked aspect when researching new materials, and recently, it became clear that the LCA analysis of new materials is an essential part to assess sustainability in a more quantitative way, despite the limitations that exist in LCA consistency and transparency.[10] From a life cycle perspective, it is known that closing loops is not always the best option because it may have negative consequences and rise the impact of a process. Therefore, the evaluation of impacts via life cycle approach is highly beneficial in providing the correct data for the assessment of new processes.[13−16]

In this framework, and taking into consideration the costs associated with the development of bioplastics, the production of biocomposite materials via minimal processing of readily available vegetable-based biomass can represent an appealing option. To this regard, polysaccharides, abundant in the waste or byproducts of the fruit and vegetable food industry, represent a renewable feedstock of raw materials that can safely biodegrade back into water and the CO_2 that was absorbed by plants for their synthesis.[17] On the other hand, protein biopolymers have good barrier properties,[18] comparable to those of PVC and PET, and can be used in the packaging industry as biodegradable plastics to help solve environmental pollution problems.[19] One example is the use of whey from the dairy industry for bioplastics, whose production process showed promising results to be economically competitive with petrochemical materials such as PP and PE.[20] Recently, new technologies for developing biocomposites based on the entire vegetables showed very promising results because they provide environmentally friendly, water-based methods to convert plant biomass, currently underutilized, into materials with promising properties for applications in packaging.[21,22] For example, the dried powder from different vegetables was completely converted into a biocomposite material with an amorphous matrix of pectin and oligosaccharides that incorporate crystalline cellulose fibers as reinforcing fillers. The developed films showed mechanical properties suitable for plastic substitution as packaging or mulching films, good oxygen barrier properties when blended with PVA, and the possibility to be thermoformed.[21−23] Thus, plant materials are beginning to make an important contribution to a circular economy.[24,25]

The most used biodegradable and bio-based materials for the production of primary packaging are polylactic acid (PLA),[26,27] starch, polyhydroxyalkanoates (PHAs), cellulose, and lignin, together with some bioplastics from fossil resources (PCL and PBAT) which are also viewed as promising because of their biodegradability. Functional polymers, such as derivatives from some polyesters, polymeric amides, and polyvinyl alcohol (PVA), are added to improve the specific performance, usually barrier properties.[18] Many of the bio-based, biodegradable polymers such as PLA and PHA had early mechanical performance drawbacks, even though bio-based plasticizers are being developed to mitigate these issues,[28] or higher prices, which have limited their acceptance thus far. The current problems associated with biopolymers are threefold: performance, processability, and cost. Although these factors are somewhat related, the problems due to performance and processability are more pronounced with polymers extracted directly from biomass. Packaging, and especially food packaging, heavily relies on the outstanding performance of oil-based plastic materials, representing one of the most challenging sectors for the application of circular economy principles in finding material alternatives.[29,30]

Therefore, bio-based, biodegradable plastics need further study and experimentation to become more widespread in the market and to replace traditional plastics. According to Bishop et al.,[31] to clearly show that bio-based plastics are more sustainable compared to the petrochemical ones, as required by The European Strategy for Plastics in a Circular Economy,[32] an accurate comparison of the environmental efficiency of these different plastics with their life cycle is crucial.

The purpose of this paper is to provide a quantitative impact analysis for the production process of biocomposite materials obtained by valorization of vegetable biomass from the food supply chain, using two water-based methods previously described.[21,22] The developed biocomposite films were further thermoprocessed in food containers to replace the traditional plastic trays made mainly with PET. The fabrication of trays was selected as application because biocomposite materials obtained from a mixed and variable biomass, such as the one available at a wholesale market, will have sufficient performance regardless of their composition. This allowed us to simplify the LCA analysis, ensuring more reliable results. Different flow sheets and scenarios were analyzed studying alternative processes and using vegetable waste from two distinct sources: fresh unsold vegetables from a local wholesale market and dried carrot pomace obtained as a byproduct of juicing. Carrot pomace represents one-third of the mass of carrots used for juicing, making it a byproduct generated in large quantities.[33,34] Currently, with limited market acceptance, it is used as a food ingredient or a substitute, with alternative options being its use as animal feed, composite, or biogas.[34,35] The company that provided the pomace for this study generates quantities in the order of 20000 tons per year of wet biomass. The wholesale market that collaborated with us produces only small quantity of waste because its primary aim is to preserve as much food as possible in the value chain. Currently, the marked discards 50 tons/year of non-edible or non-marketable vegetables. In a broader context, these scenarios are meant to represent the conversion of fresh biomass in situ where it is produced (e.g., at a farm and market) or the conversion of a byproduct from the food processing at a secondary site. Chemical process design and eco-design principles were applied, selecting a series of processing steps and their integration to form a complete manufacturing system, with the aim of precisely analyzing the process and gathering data that can be used to reliably measure

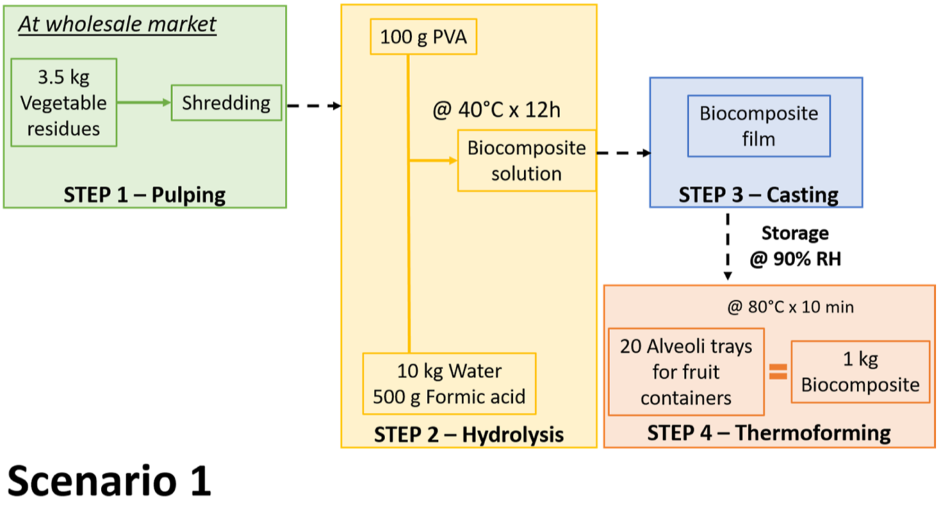

Figure 1. Scenario 1—Process flow sheet.

the process impact. Once the best process structure was established, then a Cradle-to-Gate model of the process based on life cycle assessment (LCA) methodology was developed according to the international standards ISO 14040-44,[36,37] and the process was simulated using a commercial software in order to evaluate its potential impacts along the life cycle of the process. Finally, biomaterial production process was compared to production process of conventional petroleum-based plastics used as food containers.

■ MATERIALS AND METHODS

Materials. Carrot pomace in powder form was kindly provided by Harms Food (Zeven, Germany). The pomace was received as a dried powder and used without further purification or pre-processing. Unsold vegetables (stalks and leaves of artichokes) were obtained from a local wholesale market: Mercato Generale di Genova, managed by SGM srl. HCl, formic acid (98%), and PVA (average mol wt 30,000−70,000, 87−90% hydrolyzed) were purchased from Sigma-Aldrich. Milli-Q water was used for all the experiments.

Pulping of Fresh Vegetables from Wholesale Market. The biomass from unsold vegetables was cut into smaller pieces that were then shredded with an IKA Pilotina shredder to obtain a humid pulp. This humid pulp as obtained was used for the subsequent hydrolysis steps.

Hydrolysis Steps. Films of the different biomasses were obtained after partial hydrolysis in an acidic water solution according to previously published protocols.[21,22] Briefly, the two processes are as follows: (1) hydrochloric acid process: micronized dry or humid vegetable biomass was dispersed in a 5% HCl aqueous solution at a concentration of 50 mg biomass per milliliter. The vegetable biomass was hydrolyzed for 16 h at 40 °C, after which PVA was added to the solution to achieve a concentration of 5 mg/mL, in order to have a vegetable/PVA ratio of 10:1. At the end of the hydrolysis step, the solution was dialyzed against deionized water for 72 h. (2) Formic acid process: micronized dry or humid vegetable biomass was dispersed in a 1M formic acid solution in water at a concentration of 50 mg biomass per milliliter. The vegetable biomass was hydrolyzed for 16 h at 40 °C, after which PVA was added to the solution to achieve a concentration of 5 mg/mL, in order to have a vegetable/PVA ratio of 10:1.

At the end of both processes, the dispersion was cast on a large (30 × 50 cm^2) tray and left to dry at room temperature for 48 h, to eventually obtain films.

Biocomposite Tray Fabrication. Trays were fabricated by thermoforming, according to the method developed by Perotto et al.[22] Briefly, films obtained in the previous step were conditioned in a 100% relative humidity environment for 24 h to plasticize them and were then thermoformed for 10 min at 80 °C between silicone molds.

LCA Methodology. Four different scenarios, described below, were compared at the laboratory scale. The functional unit for this comparison was the production of 1 kg of biocomposite in the form of alveoli trays (food containers). For each of the different scenario, the mathematical model to simulate the process was created using a commercial LCA software: SimaPro v.9.0. System boundaries include the phases along the supply chain from the collection of vegetable residues to the gate of tray production. Impact categories representing the water−energy−food (WEF) nexus, an indicator measuring the related cross-sectoral environmental impacts,[30] were calculated: global warming potential (GWP, 100 years, in kg CO_2 equivalents), water scarcity indicator (WSI, AWARE, in m^3 equivalents), and cumulative energy demand (CED, in MJ). CML 2001, a methodology developed by the Center of Environmental Science (CML) of Leiden University in the Netherlands, was used as the impact assessment baseline method[38] for GWP. AWARE, a regionalized water use midpoint indicator, represents the relative available water remaining per area in a watershed after the demand of humans and aquatic ecosystems has been met. AWARE is the recommended method from WULCA (working group under the umbrella of UNEP-SETAC Life Cycle Initiative) to assess water consumption impact assessment in LCA[39] and was used in our work to determine the WSI. CED of a product represents the direct and indirect energy use throughout the life cycle, including energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. In particular, this method considers both the contribution of non-renewable energy (fossil, nuclear, and non-renewable biomass) and renewable energy (renewable biomass, wind, solar, geothermal, and water). To get a total ("cumulative") energy demand, to each impact category, it was given a weighting factor of 1.[40]

LCA Case Studies. Four different flow sheets and scenarios were analyzed for the conversion of vegetable biomass into bioplastic trays. Two different sources of biomass were used (locally sourced fresh vegetables and dried carrot powder from a third company), and two different processes were used for their conversion into materials (formic acid process and HCl process) that were eventually thermoformed into trays.

In the first two scenarios, inedible portions of vegetables or non-marketable fruits and vegetables from a local wholesale market were processed with the two methods previously described. The process aims at representing the proof of concept previously developed in our labs in which fruits and vegetables discarded in a wholesale market were transformed into bioplastic films at the market facility, where the waste was generated. Films were then thermoformed to produce the alveoli trays used as fruit containers. The second two scenarios were meant to analyze the work described in our recent papers[21,22] on the

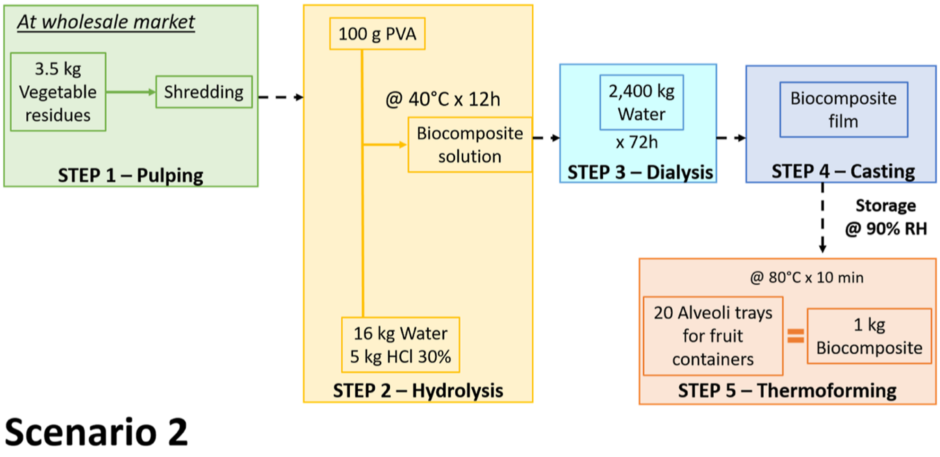

Figure 2. Scenario 2—Process flow sheet.

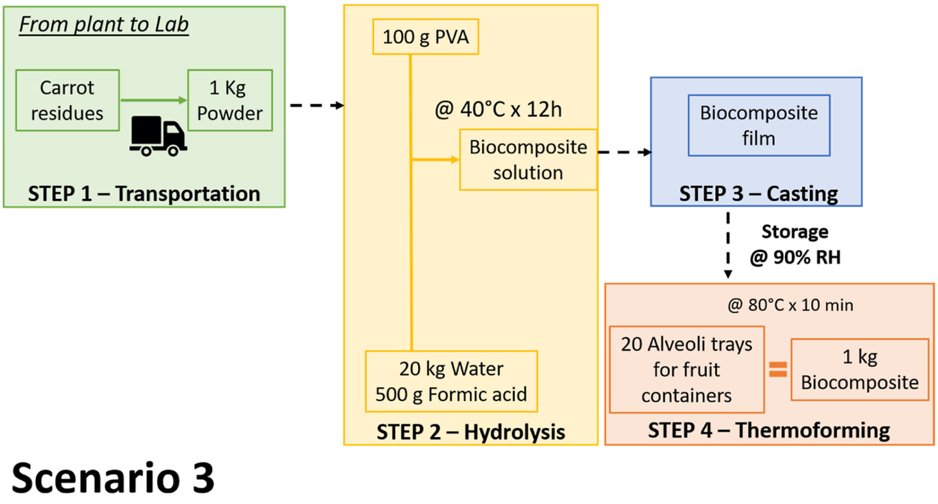

Figure 3. Scenario 3—Process flow sheet.

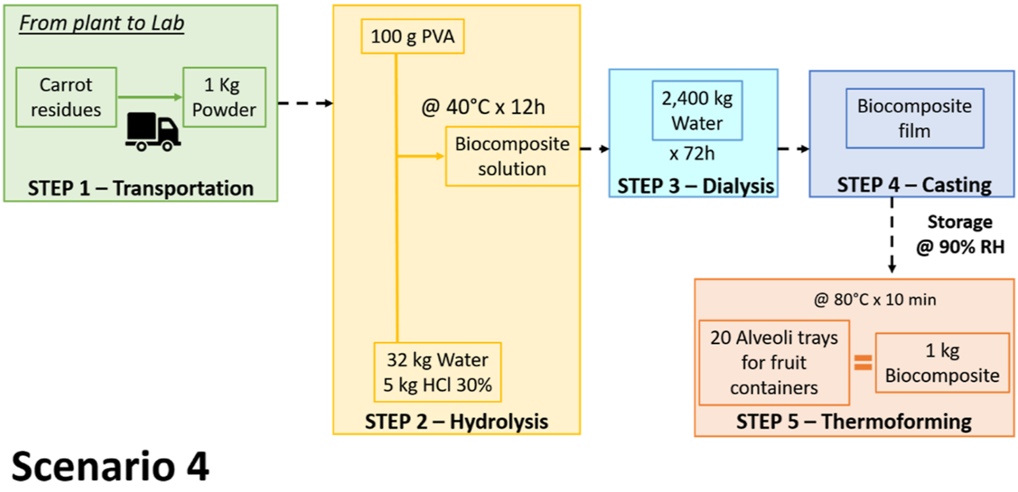

Figure 4. Scenario 4—Process flow sheet.

processing of carrot pomace and, more broadly, to represent a scenario in which the waste is produced in one food processing factory, dried to facilitate transportation, and then converted into food container in a different place. The four scenarios, described with more details, are as follows:

Scenario 1, shown in Figure 1, uses fresh vegetable waste. The films are produced after formic acid hydrolysis, and the final trays are produced by thermoforming. The four processing steps carried out at the laboratory level are as follows:

1. Pulping of the vegetables with a blender to obtain a shredded biomass with 70% water content;
2. Hydrolysis of the shredded biomass with the formic acid process previously described;

3. Casting of the solution and subsequent drying at ambient conditions to obtain a film;
4. Thermoforming of the film to obtain the alveolus tray to be used as food container.

Scenario 2, shown in Figure 2, uses fresh vegetable waste, films are produced with the HCl hydrolysis, and trays are produced by thermoforming. The five processing steps carried out at laboratory level are as follows:

1. Pulping of the vegetables with a blender to obtain shredded biomass with 70% water content;
2. Hydrolysis of the shredded biomass with the HCl process previously described;
3. Dialysis to remove residual HCl;
4. Casting of the solution and subsequent air drying to obtain a biocomposite film;
5. Thermoforming of the previously developed film to obtain the alveolus tray to be used as a food container.

Scenario 3, shown in Figure 3, uses dry powder of carrot pomace, films are produced with the formic acid hydrolysis, and trays are produced by thermoforming. The four processing steps carried out at the laboratory level are as follows:

1. Carrot pomace powder is transported to IIT laboratories (a supply distance of 1250 km is calculated);
2. Hydrolysis of the powder with the formic acid process;
3. Casting of the solution and subsequent air drying to obtain a film;
4. Thermoforming of the previously developed film obtains the alveolus tray to be used as a food container.

Scenario 4, shown in Figure 4, uses dry powder from carrot pomace, films are produced with the HCl hydrolysis, and trays are produced by thermoforming. The five processing steps carried out at the laboratory level are as follows:

1. Carrot pomace powder is transported to IIT laboratories (a supply distance of 1250 km is calculated);
2. Hydrolysis of the powder with HCl process;
3. Dialysis to remove residual HCl;
4. Casting of the solution and subsequent air drying to obtain a film;
5. Thermoforming of the previously developed film to obtain the alveolus tray to be used as a food container.

Tables 1−4 report all the inventory data collected at the laboratory level for the four scenarios described above.

Table 1. Scenario 1—Inventory Data

scenario 1	input materials [kg]	energy consumption [kWh]
step 1—pulping		0.5
step 2—hydrolysis	water: 10	0.80
	formic acid 98%: 0.5	
	PVA (polyvinyl acid): 0.1	
step 3—casting		
step 4—thermoforming		0.05

Table 2. Scenario 2−Inventory Data

scenario 2	input materials [kg]	energy consumption [kWh]
step 1—pulping		0.5
step 2—hydrolysis	water: 16	0.80
	hydrochloric acid 30%: 5	
	PVA (polyvinyl acid): 0.1	
step 3—dialysis	water: 2,400	0.17
step 4—casting		
step 5—thermoforming		0.05

Table 3. Scenario 3−Inventory Data

scenario 3	input materials [kg]	energy consumption [kWh]
step 1—transportation		0.5
step 2—hydrolysis	water: 20	
formic acid 98%: 0.5		
PVA (polyvinyl acid): 0.1	0.80	
step 3—casting		
step 4—thermoforming		0.05

Table 4. Scenario 4−Inventory Data

scenario 4	input materials [kg]	energy consumption [kWh]
step 1—transportation		0.5
step 2—hydrolysis	water: 32	0.80
	hydrochloric acid 30%: 5	
	PVA (polyvinyl acid): 0.1	
step 3—dialysis	water: 2,400	0.17
step 4—casting		
step 5—thermoforming		0.05

RESULTS AND DISCUSSION

Results of the "cradle-to-gate" LCA analysis performed for the four scenarios are reported in Tables 5−8. For each scenario, the GWP, CED, and water scarcity (WS) were calculated for each processing step.

In the case of scenario 1 (Table 5), the obtained results show that among all the three indicators considered, the hydrolysis step was the most impactful. This is due to the fact that in this step, more materials are used than in the others (in particular, the use of formic acid is quite impactful), and there is a higher energy consumption due to the long working time of the hotplate. The pulping step is less impactful but still worth to be considered: this step required no material input, but the energy consumption for shredding was still significant. It should also be considered that the casting step, in the laboratory, has no impact whatsoever, as no input material is used, and no energy is used either. Finally, the thermoforming step—which allows us to obtain the final object of the desired shape—has a low impact as it makes a negligible use of electricity. It can be noted that, considering the WSI, the impact is concentrated almost exclusively in the hydrolysis step because about 10 kg of water was used, whereas no direct water use was needed in the other steps.

Scenario 3 was very similar to scenario 1 with the exception of the biomass shredding step. While for scenario 1, the pulping of biomass was produced directly where the waste was generated; for scenario 3, its production took place in an external company where carrot pomace, a byproduct of their processing, was dried and sent to the transformation site, our lab in this case. Transport had a major impact: as shown in Table 7, transportation had a higher GWP than all other steps. Hydrolysis still had a major impact on water and energy consumption, also because the water content present in the fresh vegetables had to be replaced by additional water in the case of dried carrot powder (20 kg instead of 10 kg). The significant impact that transportation has allows us to conclude that in order to maintain the promised claim of improved

Table 5. Scenario 1—Results

			process steps			
impact categories	unit	total	pulping	hydrolysis	casting	thermoforming
GWP	kg CO_2 eq	**1.82**	0.20	1.60	0.00	0.02
CED	MJ	**48.27**	4.14	43.72	0.00	0.41
WS	m^3 eq	**3.35**	0.12	3.22	0.00	0.01

Table 6. Scenario 2—Results

			process steps				
impact categories	unit	total	pulping	hydrolysis	dialysis	casting	thermoforming
GWP	kg CO2 eq	**4.18**	0.20	3.03	0.94	0.00	0.02
CED	MJ	**93.99**	4.14	73.97	15.47	0.00	0.41
WS	m^3 eq	**53.22**	0.12	4.03	49.06	0.00	0.01

Table 7. Scenario 3—Results

			process steps			
impact categories	unit	total	transport	hydrolysis	casting	thermoforming
GWP	kg CO_2 eq	**3.63**	2.00	1.61	0.00	0.02
CED	MJ	**75.59**	31.40	43.78	0.00	0.41
WS	m^3 eq	**3.55**	0.11	3.43	0.00	0.01

Table 8. Scenario 4–Results

			process steps				
impact categories	unit	total	transport	hydrolysis	dialysis	casting	thermoforming
GWP	kg CO_2 eq	**6.00**	2.00	3.03	0.94	0.00	0.02
CED	MJ	**121.35**	31.40	74.06	15.47	0.00	0.41
WS	m^3 eq	**53.54**	0.11	4.36	49.06	0.00	0.01

sustainability, the conversion of vegetables into bioplastic must be done as close as possible to where the waste is generated.

Scenarios 2 and 4 describe a previous iteration of the conversion step, in which HCl is used to promote the controlled hydrolysis of the vegetable biopolymers. In these scenarios, a dialysis step is needed to remove HCl residues that would otherwise remain in the final material. This leads to increased water consumption in the hydrolysis step and of the overall increased energy consumption of these two scenarios. As expected, because of this, both scenarios 2 and 4 show worse performances than the related scenarios 1 and 3, respectively, confirming the improvement in sustainability caused by the substitution of HCl with formic acid.

The comparison of the four scenarios is summarized in Table 9.

Table 9. Comparison of the Analyzed Scenarios

impact category	unit	scenario 1	scenario 2	scenario 3	scenario 4
GWP	kg CO_2 eq	1.82	4.18	3.63	6.00
CED	MJ	48.27	93.99	75.59	121.35
WS	m^3	3.35	53.22	3.55	53.54

The comparison of GWP for the four scenarios shows that scenario 1 is the least impactful and is followed by scenario 3, which has slightly worst impact parameters due to the logistics: the vegetable powder is produced in a different location and has to be transported to the processing facility. Scenarios 2 and 4 are more impactful because of the additional dialysis step that required a large consumption of water. In terms of CED, scenario 1 is again the least impactful of the four considered, while scenarios 2, 3, and 4 needed considerably higher energy. Similarly to GWP, when analyzing the WS index, scenarios 1 and 3 have similar values and are significantly less impactful than scenarios 2 and 4, where the water consumption required by the additional dialysis step increases the impact.

Results summarized in Table 9 clarify that the best scenario, the one with the least impact among the four indicators, is scenario 1: conversion of fresh vegetables inside the wholesale market where they are generated using a formic acid hydrolysis. From this study, we can conclude that when processing requires a large water consumption, such as scenarios 2 and 4, it will not be suitable for the production of large-scale amounts of materials. These results also show the limitations posed by logistics: if there is a long distance between where the waste is generated and where it is converted, the transportation costs will impair the overall sustainability.

To understand if this new circular economy approach, based on replacing plastic packaging with materials produced according to scenario 1, has the capability to reduce the environmental impact of plastics, scenario 1 was compared to other biopolymers and to some of the petroleum-based plastics used for the production of fruit trays HDPE, PET, PLA, and starch biopolymer. The comparison was expanded to take into account efficiency improvement that is to be expected when scaling up a small-scale process. In our analysis, this is done by keeping material inputs constant to the lab-scale process, while we simulated a reduction in the energy consumption from 5% up to 25%.

Results are summarized in Figure 5

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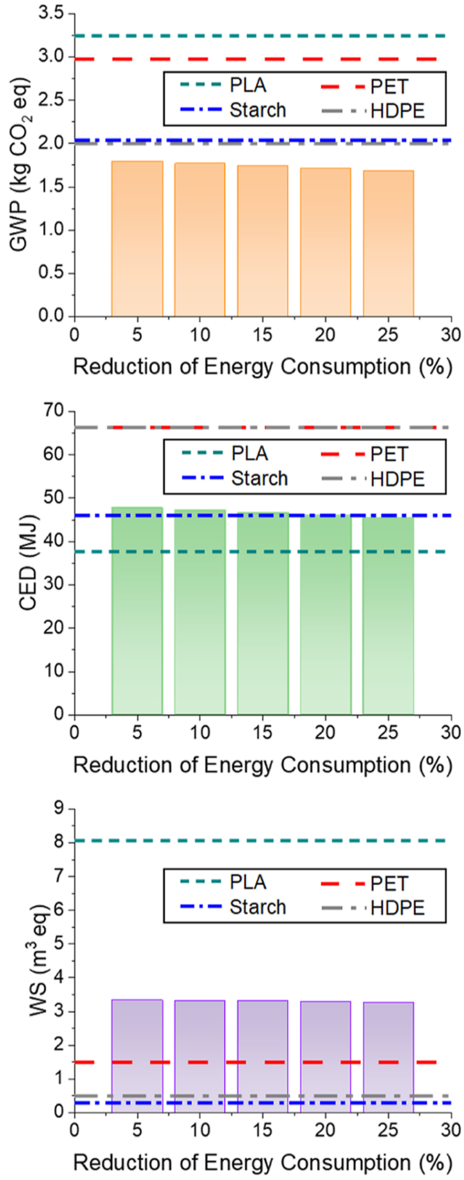

Figure 5. Comparison of GWP, CED, and WS between the biocomposites produced according to scenario 1 and different traditional materials. Efficiency improvement due to scaling up was simulated as reduction of energy consumption.

Results showed that the process modeled for scenario 1 has lower GWP than all four materials considered, especially, PLA and PET. Starch bioplastic and HDPE have similar GWP values that are always higher than scenario 1. The simulated improved efficiency due to scaling up further reduced GWP, making the new process even more competitive. When considering CED, trays produced with our vegetable biocomposite have better parameters than HDPE, similar values then starch, while PLA generally requires less energy to be produced. 20% energy consumption reduction due to efficiency allows our simulated process to have lower CED values than starch but not better than PLA. The WS index shows that our biocomposite material required more water for its production than oil-based plastics and starch. PLA, on the other hand, has higher WS index than our biocomposites. The simulated reduction due to efficiency is never enough to provide a WS index better than starch and oil-based plastics. Since the simulated reduction of energy consumption has only limited impact in reducing the environmental impact parameters, we can conclude that material consumption is their determining factor. Because of this, a significant redesign of the process is needed to further improve the environmental sustainability of process described in scenario 1. In particular, it will be important to decrease the WS index, where almost all the alternative materials considered here outperform our process. Additionally, closed cycles, in which water and formic acid used in hydrolysis can be recovered and reused, will allow us to decrease all impact parameters since the material consumption is the main source of impact.

Overall, despite our best effort to reliably measure and model the processes described here for the production of trays from upcycling discarded vegetables, their inherent small scales provide some limitations in the comparison with more consistent and reproducible industrial processes for the plastic and bioplastic production. Nevertheless, the results presented here show that the direct conversion of vegetable biomass with a water-based hydrolysis has the potential to mitigate environmental issues associated with the use of plastics, especially thanks to the lower greenhouse potential and CED.

CONCLUSIONS

In this paper, we aimed at introducing an LCA evaluation to assess the environmental impact of a new generation of vegetable biocomposites. The case study of this manuscript was the lab-scale production of vegetable-based biocomposite materials for food containers (alveoli trays) and how these new processes compare to the production of the same food container item with traditional oil-based plastics (HDPE and PET) and bioplastics (starch and PLA). The least impactful scenario—considering as indicators GWP, CED, and WS—proved to be the direct conversion of vegetable biomass generated in a wholesale fruit and vegetable market in situ, where the waste is produced, with a water-based formic acid hydrolysis (scenario 1 in the manuscript). When comparing this scenario with two traditional polymers (PET and HDPE) and two biopolymers (PLA and thermoplastic starch biopolymer), it can be seen that the fabrication of trays with vegetable biomass had better GWP parameters over all materials, better CED over PET and HDPE, and better WS over PLA. Additionally, this study provided important information on the limitations to the logistics associated with the transportation of biomass to be converted. In the example studied here, the interstate transportation of dried carrot powder had an impact similar to the transformation itself. This research, at this stage, can be used to spot areas of improvement. For instance, this analysis allowed us to understand that to achieve a further and significant improvement in the production process, a new design that allows to drastically reduce material consumption will greatly reduce impact parameters. Particularly important will be the improvement of the WSI, the impact parameter that is currently worse than the oil-based plastics considered. Despite all the limitations of simulating a lab-scale process, the performed study confirms that engineering bio-based macromolecules discarded from the food value chain as byproducts or underutilized biomass could be a first step of circular economy application representing an opportunity to provide new materials that can replace fossil fuel-based linear plastic systems.

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ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.2c02942.

Graphs showing data summarized in Tables 5−8 (PDF)

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Notes

The authors declare no competing financial interest.

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