Carbohydrate Polymers 348 (2025) 122927



Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol





Life cycle assessment (LCA) of chitin nanocrystal reinforced polylactic acid (ChNC/PLA) and polyethylene terephthalate (PET) packaging material

Murat Yanat *, Esther Voortman, Carla Buijsse, Karin Schroën

Laboratory of Food Process Engineering, Wageningen University and Research, Bornse Weilanden 9, 6708, WG, Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Chitin nanocrystals
Polylactic acid
Polyethylene terephthalate
Life cycle assessment
Nanocomposites

ABSTRACT

Bio-nanocomposites hold the promise to reduce environmental impact of plastic materials and lessen reliance on non-renewable resources as is the case for fossil-based plastics. In this study, we present chitin nanocrystal (ChNC) reinforced polylactic acid (PLA) as biodegradable polymer with natural-origin nanoparticles, enhancing the base polymer's strength. Until now, these bio-nanocomposites have been evaluated from fundamental and practical perspectives, yet, in-depth research on their environmental impact remains limited. We conducted a life cycle assessment (LCA) for upscaled ChNC production including its incorporation into PLA. We compare with the benchmark polyethylene terephthalate (PET) using ten impact indicators, primarily focusing on climate change. For PLA, PET, and ChNC/PLA (5 % particles), the production processes resulted in 3.04, 3.21, and 4.26 kg CO_2 equivalent, respectively. Recycling processes greatly enhance plastics sustainability, though practical implementation remains challenging. On that aspect, compostable PLA and ChNC/PLA materials outperform conventional plastics that end up in landfill. The climate change impact of ChNC production can be reduced by 30 to 40 % by decreasing HCl and water use during acid hydrolysis and energy used during drying compared to current laboratory conditions. These insights incorporated into ChNC/PLA production and post-use strategies can guide bio-nanocomposite production toward more sustainable practices.

1. Introduction

Plastics have become an integral part of daily life, with a staggering global production of 390 million tons in 2021 (Plastics Europe, 2022), predominantly derived from fossil fuels (Nielsen et al., 2020). Despite efforts, post-consumer recycled and biobased plastics comprised only 10 and 2.3 %, respectively, of total European production in 2021 (Plastics Europe, 2022). The longevity of fossil-based plastics, taking centuries to degrade, contributes to substantial environmental concerns. Microplastics, smaller than 5 mm, arise from plastic fragmentation and industrial processes, posing challenges in detection due to their diverse compositions and persistence in ecosystems (Osman et al., 2023). Their ingestion by marine organisms and potential transfer up the food chain may lead to toxicological and health impacts (Rose et al., 2023). Developing effective detection methods and mitigation strategies are crucial in addressing these concerns.

There is a growing demand for bio-based and biodegradable plastics made from renewable and bio-based resources, such as agricultural or marine raw materials. Their production and use imply a net CO_2 absorption (Laura et al., 2018; Morão & de Bie, 2019), that is released at the product's end-of-life. The current fabrication and composting process of bioplastics, relies on fossil fuels for energy (Mujtaba et al., 2023), which may be eliminated by transitioning to renewable energy resources in the future. These aspects make innovative plastics interesting alternatives to the fossil fuel-based plastics that are currently mostly used. The question we try to answer is whether this claim can be substantiated over the entire life cycle. We chose to investigate polylactic acid (PLA), a biodegradable polyester produced from e.g., renewable corn starch and sugar cane, because of its low environmental impact (Jayasekara et al., 2022; Kumari et al., 2022).

PLA is currently particularly used for fruit and vegetable packaging, but also for catering products, yoghurts, and prepacked meals such as salads and pasta (Ramezani Dana & Ebrahimi, 2023). To further expand PLA use in the food industry its properties need to be improved, for which chitin nanocrystal addition (ChNC) was suggested (Muñoz-Núñez et al., 2022; Yanat & Schroën, 2023). These polysaccharide materials are produced from a waste stream of the seafood industry (Casadidio et al., 2019; Younes & Rinaudo, 2015).

* Corresponding author.
E-mail address: muratyanat@gmail.com (M. Yanat).

https://doi.org/10.1016/j.carbpol.2024.122927
Received 1 February 2024; Received in revised form 24 July 2024; Accepted 26 October 2024
Available online 28 October 2024
0144-8617/© 2024 Published by Elsevier Ltd.

The incorporation of ChNC enhances the properties of the PLA matrix by influencing the interphacial layers surrounding them that in turn affect materials behavior across much larger length scales as reviewed by Colijn and co-workers (Colijn et al., 2023). These bio-nanocomposites have improved tensile strength and Young's modulus (Broers et al., 2018; Yanat & Schroën, 2023), and thermal stability and resistance to thermal degradation (Singh et al., 2020). Furthermore, the incorporation of ChNC can introduce functional properties such as antioxidant and antimicrobial activities (Salaberria et al., 2017: Yanat et al., 2022) that are particularly relevant for extending the shelf life and enhancing the safety of food products, and applications in the biomedical fields.

For food packaging products, the environmental impacts need to be examined, starting from the extraction and processing of raw materials (cradle), to manufacturing, distribution, and utilization, and recycling or disposal of the packaging material (grave) (Arvanitoyannis, 2008; Curran, 2020). The environmental performance is commonly determined by Life Cycle Analysis (LCA) (Ali et al., 2023; Bishop et al., 2021; Rosenboom et al., 2022), which is also applied to the packaging products in this study. LCA identifies the overall environmental impact, and pinpoints hotspots, thus facilitating the identification and

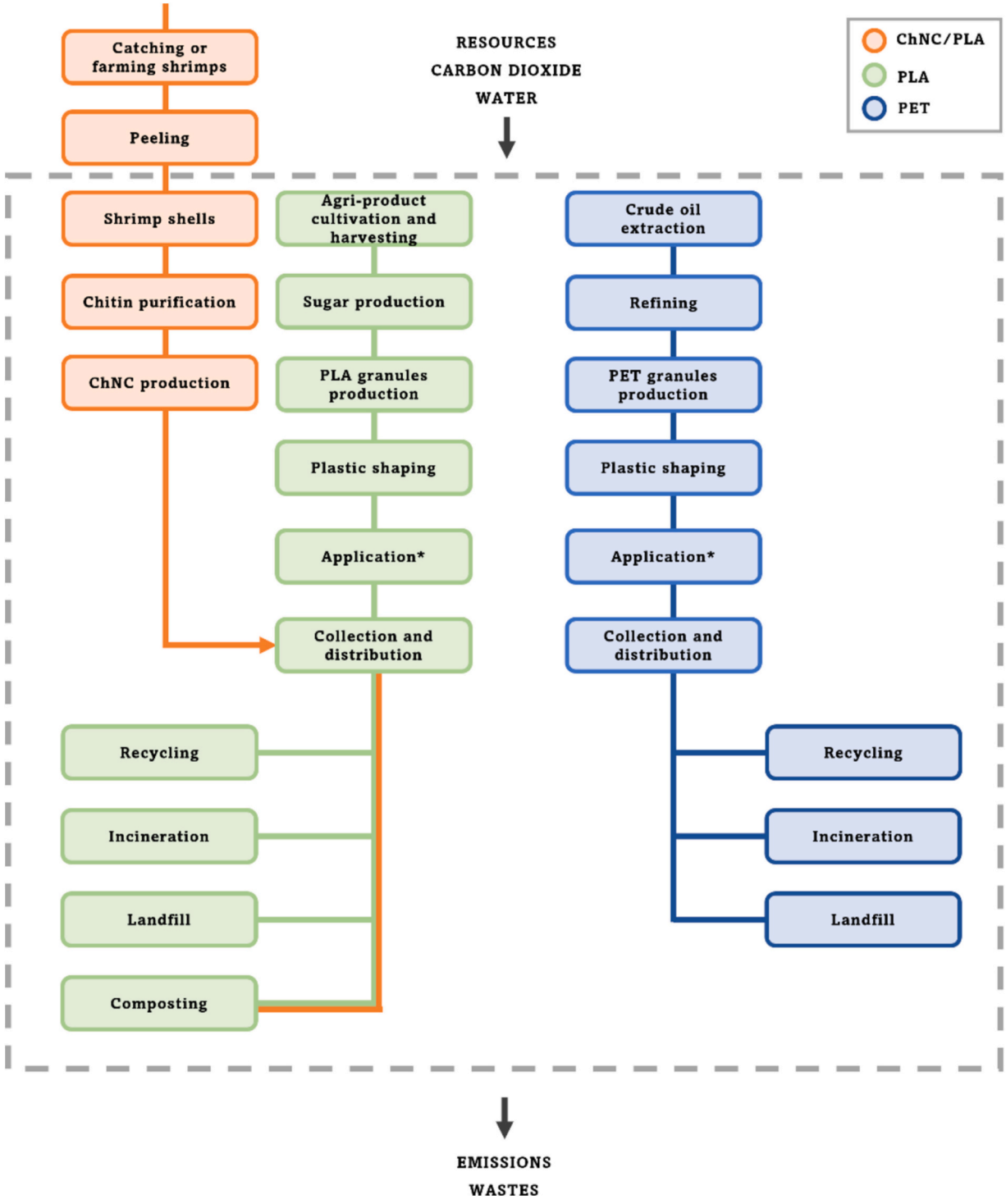


Fig. 1. System boundaries applied in LCA.

implementation of potential improvements of the product (Hellweg & Milà i Canals, 2014). The present study focusses on PLA, and ChNC/PLA and compares their environmental impact with polyethylene terephthalate (PET), the most relevant recyclable plastic for food products (Joseph et al., 2024; Osman et al., 2020; Osman et al., 2022).

LCA studies for PLA and PET packaging are available. Tamburini et al. (2021) focused on sustainability of water bottles made from PET, PLA, and aluminum (Tamburini et al., 2021). Moretti et al. (2021) studied single-use cups made of PET, PLA, and polypropylene (PP) (Moretti et al., 2021). Desole et al. (2022), compares PET and PLA bottles for pasteurized milk. For ChNC reinforced PLA, LCA has not been carried out yet, and in this paper, we collect data from industrial reports, patents, and academic papers on PLA, ChNC, and PET to do so. We consider different scenarios and their effects on the environment using a number of indicators, which are put into a broader perspective in the final section.

2. Methodology

2.1. Goal, scope, and functional unit

The goal of this LCA is to compare the environmental impact of PLA, ChNC/PLA and PET food packaging. This includes growing and harvesting of feedstock, processing into plastic pellets, making food packaging materials, and their end-of-life options. ChNC preparation is analyzed in detail, including crude chitin production from shrimp shell waste. The functional unit of 1 kg of plastic resins is set to standardize comparisons, simplify calculations, align with mass-based environmental impacts, and compare with readily available data reported per unit mass.

2.2. System boundaries

Fig. 1 illustrates the processes used and system boundaries applied to

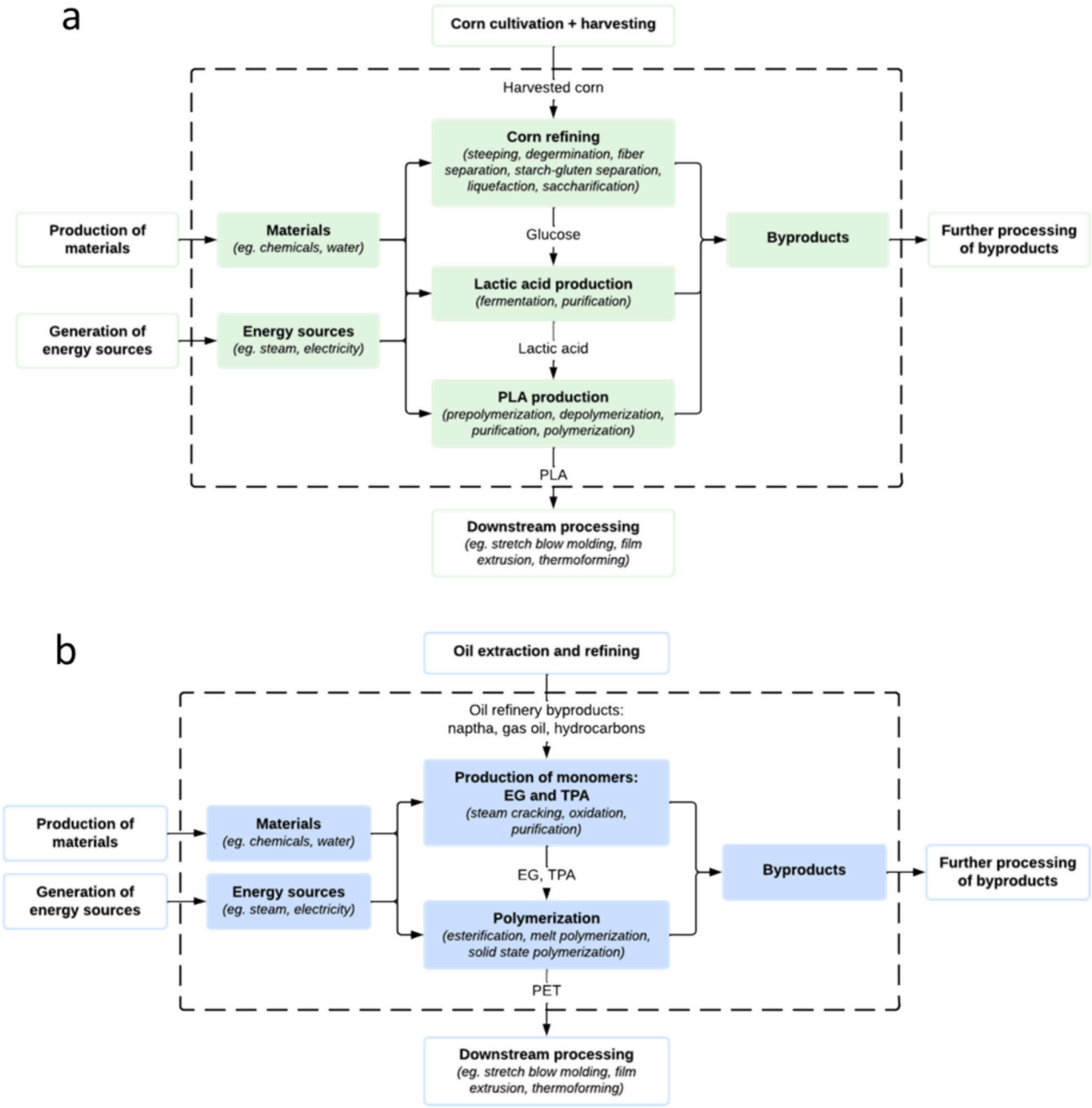


Fig. 2. Detailed flow diagrams for PLA (a) and PET (b) production.

PLA, PET, and ChNC/PLA materials. The system boundaries are cradle-to-grave for all these products, which implies that they are set from the cultivation (for PLA) or extraction of crude oil (for PET) raw materials to their end-of-life options. The retail of these packaging materials is not taken into account, and transportation of secondary and tertiary packaging are excluded. The creation and disposal of infrastructure such as machines, transport mediums, and roads, along with their maintenance, are also not considered. Shrimp shells are a significant byproduct obtained in large quantities from shrimp harvesting, and considered a byproduct. Therefore, shrimp farming/catching and peeling are considered outside system boundaries of ChNC production. For all materials the same life span is assumed.

2.3. Life cycle inventory

2.3.1. The production and end-of-life options of plastics and nanocomposites

The Ecoinvent database from Ecochain Mobius online LCA software (Ecochain Technologies B. V., Amsterdam, the Netherlands) was used as primary source for the life cycle inventory of PLA and PET production. The latest version (v2.1) of Annex C for Product Environmental Footprint (PEF) studies was used to calculate overall environmental footprint of selected materials while considering current data about end-of-life options (EoL) (European Commission, 2021; Fazio et al., 2020). According to the Product Environmental Footprint Category Rules (PEFCR) Guidance provided by the European Commission, modelling of a product's life cycle must encompass the EoL stages, whether they occur during manufacturing, distribution, retail, or after use (Fig. 2). The

Table 1
The Circular Footprint Formula (CFF) and its parameters (European Commission, 2021).

CFF = material + energy + disposal	
material	$(1-R_1)\cdot E_v + R_1\cdot\left[A\cdot E_{recycled} + (1-A)\cdot E_v\cdot\frac{Q_{Sin}}{Q_P}\right] + (1-A)\cdot R_2\cdot\left[E_{recylingEoL} - E_v^*\cdot\frac{Q_{Sout}}{Q_P}\right]$
energy	$(1-\mathrm{B})\cdot R_3\cdot\left[E_{ER} - LHV\cdot X_{ER,heat}\cdot E_{SE,heat} - LHV\cdot X_{ER,elec}\cdot E_{SE,elec}\right]$
disposal	$(1-R_2-R_3)\cdot E_D$
A:	allocation factor of burdens and credits between supplier and user of recycled materials
B:	allocation factor of energy recovery processes: it applies both to burdens and credits
Q_{Sin}:	quality of the ingoing secondary material, i.e., the quality of the recycled material at the point of substitution
Q_{Sout}:	quality of the outgoing secondary material, i.e., the quality of the recyclable material at the point of substitution
Q_P:	quality of the primary material, i.e., quality of the virgin material
R_1:	the proportion of material in the input to the production that has been recycled from a previous system
R_2:	the proportion of the material in the product that will be recycled (or reused) in a subsequent system.
R_3:	the proportion of the material in the product that is used for energy recovery at EoL
$E_{recycled}$:	specific emissions and resources consumed (per unit of analysis) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process
$E_{recyclingEoL}$:	specific emissions and resources consumed (per unit of analysis) arising from the recycling process at EoL, including collection, sorting and transportation process
E_v:	specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material
E^*_v:	specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials
E_{ER}:	specific emissions and resources consumed (per unit of analysis) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery)
$E_{SE,heat}$, $E_{SE,elec}$:	specific emissions and resources consumed (per unit of analysis) that would have arisen from the specific substituted energy source, heat and electricity respectively
E_D:	specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material at the EoL of the analyzed product, without energy recovery
$X_{ER,heat}$, $X_{ER,elec}$:	the efficiency of the energy recovery process for both heat and electricity
LHV:	Lower Heating Value of the material in the product that is used for energy recovery

Circular Footprint Formula (CFF) should be employed to address multi-functionality in recycling, re-use, and energy recovery scenarios.

The EoL options from Annex C (V 2.1) for Product Environmental Footprint (PEF) were used to calculate CFF of PET. According to this guideline, 42 % of PET material is recycled in the European Union, while 58 % is considered municipal waste. The large majority (55 %) of municipal waste goes to landfill, and the rest is used for energy recovery by incineration. The equation and parameters of CFF are provided in Table 1.

2.3.2. ChNC production

Crude chitin powder is currently available on the market, while chitin nanocrystals are not. Therefore, data for ChNC production, from shrimp shell waste to crude chitin powder and eventually to ChNC, were collected from peer-reviewed scientific papers (Casadidio et al., 2019; Lopes et al., 2018; Meramo-Hurtado et al., 2020; Muñoz et al., 2018; Riofrio et al., 2021; Younes & Rinaudo, 2015), and our experimental results from previous studies (Colijn et al., 2022; Yanat et al., 2022; Yanat, Colijn, et al., 2023). The process and mass flows were modelled accordingly.

Fig. 3 illustrates ChNC production including materials used during the process. The process begins with washing the shrimp shells to remove unwanted substances, after which they are dried and grinded. Next, these flakes are treated with NaOH solution at 100 °C for 1 h, during which the proteins present are removed. HCl and NaOCl are used to eliminate minerals and color pigments. After each step, centrifugation is applied, and the supernatant removed. The crude chitin powder is obtained after drying. All this information is taken from the above-mentioned literature.

For the production of ChNC, we use conditions from earlier work. Acid hydrolysis (HCl, 3 M) is the first step in ChNC production leading to depolymerization of the chitin structure into nano-sized chitin material. This step is typically carried out at temperatures between 80 and 100 °C for 1.5 h (Yanat et al., 2022; Yanat & Schroën, 2023). Centrifugation is used to remove residual acid solution. Ultrasonication is applied to facilitate the separation of amorphous chitin in the next centrifugation step (1200 ×*g*, for 20 min), allowing ChNC to be collected from the supernatant. The ChNC is obtained through a freeze-drying step.

The modelled process requires 44.2 kg wet weight shrimp shells (corresponding to 2.6 kg crude chitin powder) per kilogram of ChNC. The production consumes 20.5 kg of HCl (32 %), 2.6 kg of NaOH, approximately 84 kWh of electricity, and generates 293 L of wastewater and 1.82 kg CO_2 emission, per kg ChNC. Please note that the recovery and reuse of the residual acid/base solutions and water resources are not considered in the current study due to their complexity and the absence of comparable processes.

2.4. Life cycle impact assessment

The standardized LCA methodological framework of The International Organization for Standardization (ISO) norms 14040, and 14044 was used in this study (ISO I, 2006a, 2006b). The life cycle impact assessment was conducted by integrating the existing impacts of plastic production, the modelled ChNC production process, and both current and future end-of-life options. This assessment was carried out using the Ecochain Mobius online LCA software and the Environmental Footprint (EF) V 3.0 method. Table 2 shows the selected impact categories, their units and indicators for the life cycle impact assessment.

3. Results and discussion

3.1. ChNC production

Table 3 shows how each production step in the process affects environmental impact per kg ChNC made. Both the production of the crude chitin powder and nano-sized chitin are specified. The steps with high impact are colored in red, moderate and low impact steps are represented in orange and yellow, and very low-impact ones are coded green, respectively. The results clearly show that demineralization, deproteinization, and acid hydrolysis that all involve concentrated acid and base treatment, play a major role in the environmental impact. Furthermore, the freeze-drying step is very energy-intensive. Sonication,

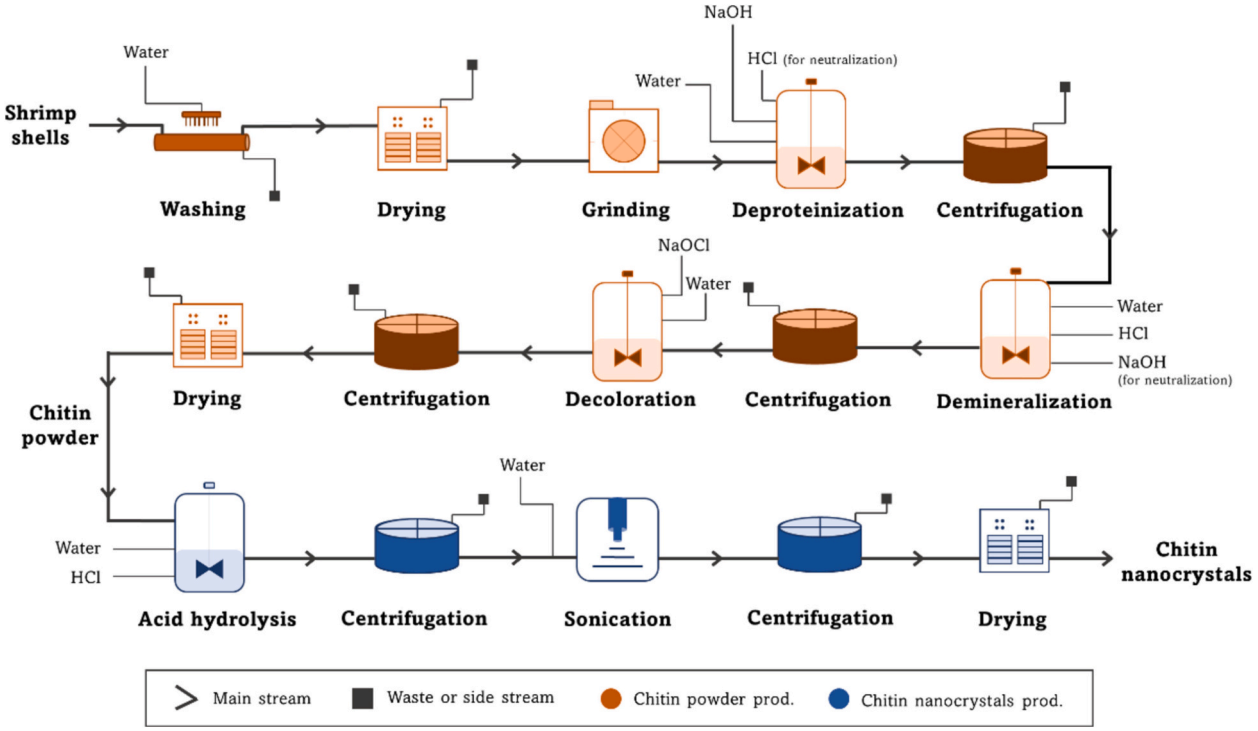


Fig. 3. Flow diagram of ChNC production from shrimp shells.

Table 2
The list of selected impact categories, their units and indicators/method.

Impact category	Unit	Indicators/method
Climate change	kg CO_2 eq	Radiative forcing as Global Warming Potential (GWP100)
Ozone depletion	kg CFC-11 eq	Steady-state ozone depletion potential
Human toxicity, cancer	CTUh	Comparative Toxic Unit for human (CTUh)
Human toxicity, non-cancer	CTUh	Comparative Toxic Unit for human (CTUh)
Resource use, fossils	MJ	Abiotic resource depletion fossil fuels (ADP-fossil)
Ecotoxicity, freshwater	CTUe	Comparative Toxic Unit for ecosystems (CTUe)
Land use	Dimensionless, Pt	Soil quality index
Water use	m^3 depriv.	User deprivation potential (deprivation-weighted water consumption)
Acidification	mol H^+ eq	Accumulated Exceedance
Ionising radiation	kBq U-235 eq	Human exposure efficiency relative to U235

decoloration, and the final step of crude chitin powder production, fluidized bed drying, are much less influential. Washing shrimp shells, drying (open air), and grinding, them, and centrifugation have a low environmental impact across categories, and can be safely disregarded.

The environmental impact of process steps follows a similar trend across categories, with only few exceptions. We therefore decided to focus our interpretation primarily on climate change since this is the most widely used impact category in life cycle assessments, thus linking to relevance for scientists and industry. The overall climate change impact of producing 1 kg of ChNC is 27.41 kg CO_2 equivalent, of which 11.83 kg CO_2 equivalent is for chitin powder production. Remarkably, the freeze-drying process contributes 30 % of the climate change impact, with 8.30 kg CO_2 equivalent, followed by demineralization and acid hydrolysis, both contributing around 23 %. The deproteinization process conducted at 100 °C with NaOH treatment was considerably less influential at 2.58 kg CO_2 eq.

3.2. Plastic/nanocomposite resins production

Table 4 compares the environmental impact of 1 kg plastic or nanocomposite resin production. PLA demonstrates comparable sustainability performance to PET in many categories with the exception of land and water use. The addition of ChNC to PLA increases the environmental impact in various categories. Most notably the CO_2 equivalent increases from 3.04 to 4.26 kg for addition of 5 % ChNC to PLA (40 % increase). In Fig. 4, the contribution of ChNC and PLA production to the environmental impact of the ChNC/PLA nanocomposite are presented. In general, ChNC has an average 30 % impact on the environmental effects of nanocomposites, and this is relatively high given the fact that only 5 % ChNC are used. This impact can be significantly higher, reaching up to approximately 70 %, in the case of ozone depletion, and human toxicity.

3.3. End-of-Life (EoL) options

Unlike PET that ends up in landfill, PLA material can be sent to industrial composting facilities where it can biodegraded in a short period of time (van der Zee & Molenveld, 2020) at temperatures of 55–70 °C, adequate moisture, and aeration (Danyluk et al., 2010). In earlier work we found that addition of ChNC to PLA films does not adversely affect the biodegradability of PLA (Yanat, Muthurajan, et al., 2023). For PLA's end of life, recirculation (CFF) is based on the after-use data of PET. The ChNC/PLA nanocomposite is considered to be treated in a composting facility. Table 5 summarizes the EoL options considered in this study. For the parameters used in the CFF calculations, please refer to Appendix Table A1.

Table 6 presents the climate change impact of the PET, PLA and ChNC/PLA resins, including post-use management per 1 kg of material. For PET resins, the climate change impact is 3.02 kg CO_2 equivalent, due to PET's relatively high recycling rate of 42 %. The kg CO_2 equivalent for PLA is slightly lower if post-use management is established with the same recycling-energy recovery-landfill (composting) ratio as PET; producing the material needs lower kg CO_2 equivalent, while incineration needs a bit more due to the lower caloric value of PLA (Appendix

Table 3
The results of the LCA method (Environmental Footprint V3.0) express the contribution of each step in ChNC production to the environmental impact of this material. Color codes indicate the level of impact: green for very low, yellow for low, orange for moderate, and red for high impact.

Impact categories	Unit	Washing	Drying (open air)	Grinding	Deprotein ization	Demineral ization	Decolorati on	Drying	Acid hydrolysis	Sonication	Centrifug ation	Freeze-drying
Climate change	kg CO_2 eq	0.11	0.01	0.36	2.58	6.40	0.74	1.63	6.38	0.91	0.00	8.30
Ozone depletion	kg CFC-11 eq	8.22×10^{-9}	4.95×10^{-10}	1.74×10^{-8}	1.47×10^{-6}	2.97×10^{-6}	4.50×10^{-7}	7.80×10^{-8}	3.90×10^{-6}	4.21×10^{-8}	2.14×10^{-11}	3.99×10^{-7}
Human toxicity, cancer	CTUh	2.42×10^{-10}	1.81×10^{-12}	5.86×10^{-11}	1.51×10^{-9}	4.67×10^{-9}	4.86×10^{-10}	2.63×10^{-10}	5.53×10^{-9}	1.74×10^{-10}	8.84×10^{-14}	1.34×10^{-9}
Human toxicity, non-cancer	CTUh	1.00×10^{-8}	5.90×10^{-11}	2.02×10^{-9}	1.43×10^{-7}	8.06×10^{-7}	2.67×10^{-8}	9.05×10^{-9}	1.33×10^{-6}	4.78×10^{-9}	2.43×10^{-12}	4.62×10^{-8}
Resource use, fossils	MJ	0.92	0.11	4.74	34.6	97.2	10.5	21.3	121	12.1	6.13×10^{-3}	109
Ecotoxicity, freshwater	CTUe	4.29	6.84×10^{-2}	4.25	61.4	142	62.3	11.9	171	9.38	4.77×10^{-3}	97.5
Land use	Pt	0.5	2.77×10^{-2}	0.75	4.62	6.53	0.85	3.37	7.36	1.71	8.69×10^{-4}	17.2
Water use	m3 depriv.	3.61	1.37	3.49×10^{-2}	4.14	8.29	1.39	2.69×10^{-1}	12.9	8.87×10^{-2}	4.50×10^{-2}	1.45
Acidification	mol H^+ eq	6.98×10^{-4}	3.13×10^{-5}	7.85×10^{-4}	1.53×10^{-2}	4.51×10^{-2}	4.75×10^{-3}	3.52×10^{-3}	5.89×10^{-2}	1.81×10^{-3}	9.19×10^{-7}	1.80×10^{-2}
Ionising radiation	kBq U-235 eq	9.93×10^{-3}	2.96×10^{-3}	3.23×10^{-2}	0.44	1.51	0.16	0.15	2.08	8.05×10^{-2}	4.09×10^{-5}	7.43

Table 4
The environmental impact of 1 kg plastic/nanocomposite resins according to Environmental Footprint V3.0 method.

Impact category	Unit	PET	PLA	ChNC/PLA
Climate change	kg CO_2 eq	3.21	3.04	4.26
Ozone depletion	kg CFC-11 eq	1.52×10^{-5}	2.22×10^{-7}	6.78×10^{-7}
Human toxicity, cancer	CTUh	1.98×10^{-9}	2.12×10^{-9}	2.73×10^{-9}
Human toxicity, non-cancer	CTUh	3.63×10^{-8}	6.09×10^{-8}	1.77×10^{-7}
Resource use, fossils	MJ	71.41	37.84	56.51
Ecotoxicity, freshwater	CTUe	45.03	119.19	141.82
Land use	Dimensionless, Pt	7.61	33.91	34.36
Water use	m^3 depriv.	1.52	4.38	5.84
Acidification	mol H^+ eq	1.40×10^{-2}	2.06×10^{-2}	2.70×10^{-2}
Ionising radiation	kBq U-235 eq	1.58×10^{-1}	2.41×10^{-1}	4.88×10^{-1}

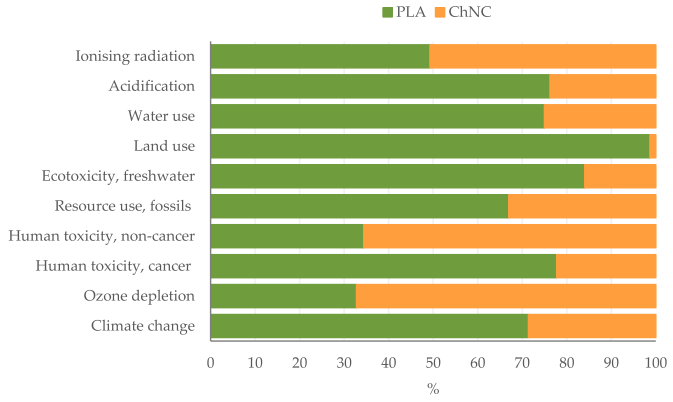


Fig. 4. The contributions of PLA and ChNC production to the environmental impact of ChNC/PLA nanocomposite resins.

Table 5
The EoL scenarios considered in this study.

Material	EoL utilization	Code
PET	42 % recycling, 26.1 % energy recovery, 31.9 % landfill	PET (CFF)
PLA	42 % recycling, 26.1 % energy recovery, 31.9 % landfill	PLA (CFF)
ChNC/PLA	100 % composting	ChNC/PLA (COM)

Table 6
The climate change impacts of 1 kg plastic and nanocomposite resins including their end-of-life management.

	Material	Energy	Disposal	Total
PET (CFF)	2.84	0.13	0.05	3.02 kg $CO_{2\ eq.}$
PLA (CFF)	2.70	0.17	0.01	2.88 kg $CO_{2\ eq.}$
ChNC/PLA (COM)	4.26	–	0.07	4.33 kg $CO_{2\ eq.}$

Table A1). PLA is suitable for industrial composting, which decreases the climate impact by 0.18 kg CO_2 eq. This underscores the significance of composting as an end-of-life option, also for PLA/ChNC of which the material production is relatively high for the non-optimized production methods that can be improved as discussed in the next section. Bare to keep in mind that waste collection and post-processing infrastructures for PLA and other biodegradable plastics are not at the level described here, but the benefits that can be derived are obvious.

3.4. Sustainable adjustments to ChNC production

Researchers have primarily focused on preparing the smallest individual nanocrystals possible, and this has influenced the selection of production methods, including the quantity of chemicals used, the drying method, and so forth. The production of ChNC is far from optimized, and various improvements are possible, thus moving from desired nanocrystal properties to sustainability. For instance, in the acid hydrolysis step, the ratio of chitin to HCl (3 M) is relatively high (1/75), and this can be reduced to 1/25. Furthermore, the impact of freeze-drying can be reduced by using pre-concentration steps, or alternative drying methods. In line with this, Table 7 shows two suggestions to make ChNC production more sustainable (reduction of acid, and alternative drying method).

Fig. 5 shows the climate change impact for these methodologies. Our 'standard' production method exhibits a climate change impact of 27.41 kg CO_2 equivalent per 1 kg ChNC produced. In a scenario where the amount of HCl is reduced to one-third in the acid hydrolysis step, and ChNC are dispersed in less water prior to freeze-drying, the climate change impact of 1 kg ChNC may decrease by 30 % to 19.18 kg CO_2 equivalent. When applying a low-energy fluidized-bed drying step instead of freeze-drying, the climate change impact can be reduced to 16.28 kg CO_2 equivalent for 1 kg ChNC. Although it sounds simple, changing the method, it may lead to side effects. Nanoparticle aggregation is more extensive when using other drying methods which affects mechanical and barrier characteristics of the nanocomposite, and ultrasonication is essential for reaching a higher yield of ChNC which needs to be weighed against its environmental impact that is high at almost 0.91 kg CO_2 equivalent.

It is important to mention that in the inventory phase of the life cycle analysis, we did not assess the by-products generated in crude chitin powder production such as protein- and mineral-rich mixtures for their value or auxiliary industrial processes like wastewater recycling. Some studies have demonstrated the feasibility of using the by-products of crude chitin powder production in agriculture, such as the protein-rich stream formed after deproteinization that can be applied as fertilizer, or calcium carbonate-($CaCO_3$) and other mineral-rich streams formed downstream of the demineralization step that can be used for various applications (Muñoz et al., 2018; Piekarska et al., 2023). Additionally, wastewater reuse in the process was reported (Lopes et al., 2018).

As acids and bases play a key role in the environmental impact of crude chitin powder production, the emerging biological methods for the production of ChNC may be considered in future LCA's. These methods employ various microbial fermentations to eliminate proteins and minerals (Islam et al., 2023; Kaur & Dhillon, 2015; Sixto-Berrocal et al., 2023). These are interesting options, but at the time of writing have not reached sufficient maturity to be included in the LCA.

3.5. Limitations of the study

It is good to point out that considerable regional variation in quality

Table 7
The current and suggested more sustainable methods and parameters considered for ChNC production.

	chitin/HCl ratio (*w/v*) in acid hydrolysis	Drying method and input material
Current method	1/75	Freeze-drying/1 kg ChNC +15 kg water
Alternative I	1/25	Freeze-drying/1 kg ChNC +7 kg water
Alternative II	1/25	Fluidized-bed drying / 1 kg ChNC +3 kg water

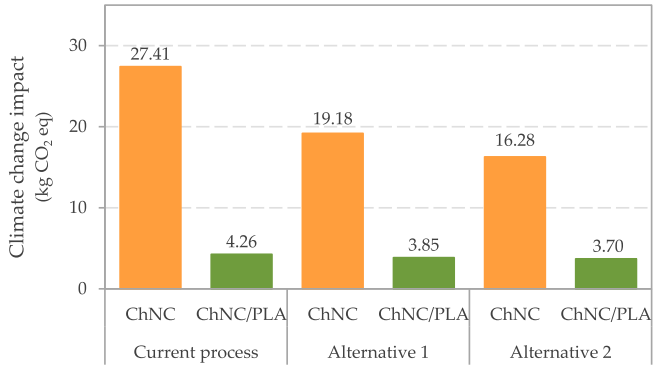


Fig. 5. The climate change (kg CO_2 eq) impact of current and suggested ChNC production processes.

and availability of data may occur. These relate to differences in production methods and environmental regulations which may limit the direct use of the data presented here. And this also holds for the maturity of the production processes that is high for PER, and much less developed for emerging materials like PLA with ChNC.

This assessment does not encompass the ecological consequences of plastic pollution in nature due to the lack of emission data, long-term hazards and toxicity of macro/micro/nano-plastics, and impact assessment models. Ideally this will also be included in the future, since one of the major concerns about conventional fossil-based plastics is nature pollution.

4. Conclusion

In this study, we employed LCA to quantify the environmental impact of PLA nanocomposites formed by incorporating ChNC in PLA, and PET expressed as kg CO_2 eq. This assessment included production processes and end-of-life options. PLA has slightly lower kg CO_2 eq compared to PET, and ChNC/PLA nanocomposite is quite higher because of the low technical readiness level of the production of ChNC, for which various improvements were suggested. This includes reduced chemical usage, application of biological methods, and considering alternative processing options (e.g., choice of drying method). In order to make biodegradable plastics a success, policymakers and industrial stakeholders need to become more aware of the need for composting infrastructure to facilitate proper disposal. Creating public awareness about responsible disposal practices is also essential. The paper provides guidance for the sustainable production and waste management of these innovative biobased materials.

Funding

This work was supported by TKI Agri & Food project number HT-17215, and also was carried out under project number A17020 as part of the research program of the Materials Innovation Institute (M2i) which is supported by the Dutch government. Funding for this research was obtained from Yparex, Oerlemans Packaging B.V., Koninklijke Peijnenburg B.V., Heineken, and Jacobs Douwe Egberts. The authors are thankful for the financial support for the PhD training of Murat Yanat by the Republic of Türkiye Ministry of National Education.

CRediT authorship contribution statement

Murat Yanat: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Esther Voortman:** Methodology, Investigation. **Carla Buijsse:** Methodology, Investigation. **Karin Schroën:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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.

Appendix A

Table A1
CFF parameters used in this study

	PET	PLA	Unit	Source
A:	0.5	0.5	proportion	Annex C (V2.1)
B:	0	0	proportion	Annex C (V2.1)
Q_{Sin}:	0.9	0.9	proportion	Annex C (V2.1)
Q_{Sout}:	0.9	0.9	proportion	Annex C (V2.1)
Q_P:	1	1	proportion	Annex C (V2.1)
R_1:	0	0	proportion	Annex C (V2.1)
R_2:	0.42	0.42	proportion	Annex C (V2.1)
R_3:	0.261	0.261	proportion	Annex C (V2.1)
$E_{recycled}$:	1.15	1.15	kg CO_2 eq	Ecoinvent database + this LCA
$E_{recyclingEoL}$:	1.15	1.15	kg CO_2 eq	Ecoinvent database + this LCA
E_v:	3.21	3.04	kg CO_2 eq	Ecoinvent database + this LCA
E^*_v:	3.21	3.04	kg CO_2 eq	Ecoinvent database + this LCA
EER:	2.37	2.37	kg CO_2 eq	Ecoinvent database + this LCA
$E_{SE,heat}$:	0.07	0.07	kg CO_2/MJ	Ecoinvent database + this LCA
$E_{SE,elec}$:	0.16	0.16	kg CO_2/MJ	Ecoinvent database + this LCA
ED:	0.15	0.07	kg CO_2 eq	Ecoinvent database + this LCA
$X_{ER,heat}$:	0.35	0.38	proportion	(Aryan et al., 2021; Tran & West, 2021)
$X_{ER,elec}$:	0.35	0.38	proportion	(Aryan et al., 2021; Tran & West, 2021)
LHV:	22.95	19.50	MJ/kg	(Castro-Aguirre et al., 2016; Laußmann et al., 2010)

Data availability

Data will be made available on request.

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