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Insect-based biopolymers from Orthoptera: An emerging resource for sustainable and active food packaging

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ABSTRACT

Background: The challenges of the current era in food packaging have led to a continuous diversification of sources of biopolymers. Edible Orthopterans have garnered significant interest worldwide as potential sources of biopolymers for the production of biodegradable and active packaging. These insect species have emerged as a potential and sustainable substitute for conventional protein and chitosan sources due to their high nutritional content and eco-friendly cultivation methods.

Scope and approach: This review explores the recent development of sustainable sources of biopolymers, focusing on the edible Orthopterans. We elucidated the main edible Orthoptera species used as the sources of biopolymers for food packaging, extraction methods of biopolymers from Orthopterans, fabrication of packaging materials and their characteristics. Moreover, we analyzed the current applications of these packaging materials for food preservation. Furthermore, we proposed a critical analysis of the health issues, consumer acceptance, legislation and commercialization, along with the future directions.

Key findings and conclusions: *Acheta domesticus*, *Grylloides sigillatus* and *Locusta migratoria* are the Orthopterans used as sources of biopolymers for the production of packaging materials. Chitosan and proteins are the major Orthopteran-derived biopolymers used for the production of sustainable, edible and bioactive food packaging materials. Emerging technologies have shown potential to enhance extraction efficiency while preserving the functionality of the biopolymers. These biopolymers exhibit remarkable potential for the development of food packaging materials, due to their biodegradability, biocompatibility, and functional properties. More research initiatives and awareness are needed to facilitate the implementation of Orthopteran-derived biopolymers as active packaging materials.

1. Introduction

The continuous use of traditional plastic packaging causes immutable consequences on the environment and the health of living. Growing awareness of these consequences, together with consumer commitment to sustainability, has led to the development of innovative, sustainable, biodegradable, edible, smart and bioactive food packaging materials (Weng et al., 2023). This implies the search for sustainable and bioactive sources of biopolymers with the ability to be used as food packaging materials. Insects appear as an ideal source of biopolymers such as proteins, carbohydrates and lipids that can be used to prepare

edible films and coatings (Weng et al., 2023; Purkiewicz et al., 2025; Zafar et al., 2024). Insect ingredients as edible food packaging compensate for the nutritional needs and augment green environmental protection (Weng et al., 2023).

Orthoptera, an order of insects encompassing grasshoppers, locusts, crickets, and katydids, despite being assessed as pests at the global scale (Gardiner, 2018; Jago, 1998), are fascinating insects widely distributed worldwide, studied and valued for their ecological and nutritional roles. They are characterized by chewing mouthparts, long hind legs adapted for jumping, and, in many species, their strong tegminal stridulation, produced by rubbing their forewings (tegmina). The order Orthoptera is

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the current research focus for the extraction of biopolymers useable for the preparation of food materials (Magara et al., 2021; Weng et al., 2023). Orthoptera are part of sustainable agricultural systems and can be valorized both as food and as a source of biopolymers from their exoskeletons. Using orthoptera-derived materials helps create circular bioeconomies within food systems, reducing waste and improving food preservation through active packaging that extends shelf life. Developing biopolymer extraction and bioplastic production technologies from orthoptera promotes green innovation in materials science and packaging industries. This supports the Sustainable Development Goal (SDG) 9 by encouraging bio-based industrial processes and supporting sustainable technological infrastructure. Furthermore, the orthoptera-based biopolymers represent renewable, biodegradable alternatives to petroleum-based plastics, contributing to SDG 12 by reducing plastic pollution, promoting recycling and valorization of insect biomass, and encouraging responsible resource management in food and packaging industries. Moreover, insect farming emits significantly fewer greenhouse gases and requires less water and land compared to livestock or synthetic plastic production, which helps mitigate SDG 13, as it supports low-carbon material innovation and contributes to climate change mitigation. Additionally, replacing non-biodegradable packaging materials with biodegradable insect-based films reduces terrestrial and marine pollution, aligns with the SDGs 14 and 15, which help protect ecosystems from microplastic contamination and supports biodiversity.

Biopolymers, including chitin, chitosan and proteins, have been extracted from different species of Orthoptera and applied for the production of sustainable and bioactive food packaging materials (Chae et al., 2018; Inthorn et al., 2024; Lone, Bhat, et al., 2025; Singh et al., 2024). Recent studies have highlighted the potential of orthoptera-based biopolymer films and coatings not only as sustainable packaging materials but also as active packaging systems capable of extending the shelf

life of food products through antimicrobial or antioxidant functionalities.

This review aimed to evaluate the potential of orthopterans as sources of biopolymers convertible into sustainable, edible and bioactive food packaging materials. For this purpose, we comprehensively highlighted the insights on Orthoptera species that are legally and industrially bred for feed and food uses and the extraction of biopolymers from these Orthoptera species for the production of packaging materials. Additionally, we investigated the characteristics of the packaging materials produced from the Orthoptera-based biopolymers and proposed a critical analysis of the health issues, consumer acceptance, legislation and commercialization, as well as some comments on the future directions.

2. Brief insight into orthoptera species used as biopolymer sources for food packaging materials

Orthopteran species have recently gained attention as sustainable sources of biopolymers, particularly protein, chitin, and its derivative chitosan, for use in food packaging materials. As of 2020, 370–420 billion orthopterans were slaughtered or sold live, with crickets being the most common (Rowe et al., 2024). Some Orthoptera Gryllidae (*Acheta domesticus*, *Grylloides sigillatus* and *Gryllus assimilis*) are currently legally admitted and farmed in Europe as feed for pigs, poultry, aquaculture, and pets (Regulation (EU) 2017/893) (Fig. 1a, b, c).

In Europe, some other Orthoptera as *A. domesticus* (Gryllidae) and *L. migratoria* (Acrididae), are now admitted as food and farmed (Regulations (EU) 2021/1975, 2022/188, and 2023/5) (Fig. 1a–d). Only two commercial firms are currently authorized by the European Food Safety Authority (EFSA) to produce and market orthopterans for food in Europe: the Dutch “Fair Insect BV” and the Vietnamese “Cricket One Co Ltd”. Orthoptera farming has a markedly lower ecological footprint

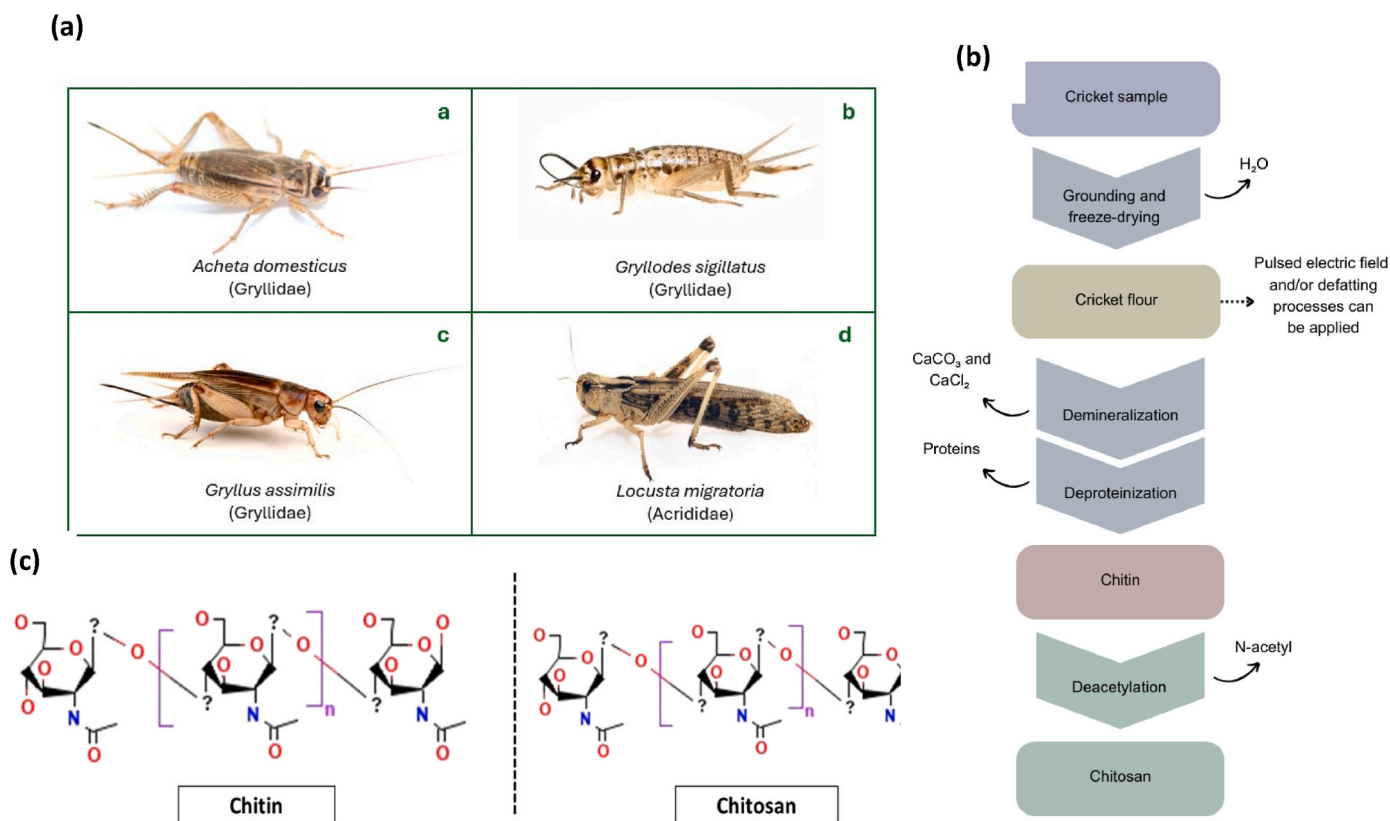


Fig. 1. (a) Orthoptera authorized in EU for feed (a, b, c) and food (a, d). Pictures by a. Brian Gratwicke, b. Dave Huth, c. Antagain, d. Manfred Beutner; (b) Overview of chitosan purification traditional processes from crickets; (c) Chemical structure of chitin and chitosan.

compared to conventional livestock. Edible insects require less land, water, and feed, and they emit fewer greenhouse gases and are now considered as a scalable solution for food and feed production (Berggren et al., 2019; Oonincx et al., 2010; Purkiewicz et al., 2025). Numerous facilities producing edible insects have been established on different scales in Europe and around the world. The insect farming industry continues to grow and is expected to become more profitable (Verner et al., 2021). Recent investigations showed that *A. domesticus*, *G. sigillatus* and *L. migratoria* are the common Orthoptera species used as sources of biopolymers for the formulation of sustainable, edible and bioactive food packaging materials (Lone, Bhat, et al., 2025; Lone, Kumar, et al., 2025; Malm et al., 2021; Zhang et al., 2022).

3. Extraction methods of orthoptera-based biopolymers

Orthoptera species are great sources of biopolymers such as chitin, chitosan, and proteins. The growing interest in Orthoptera-derived materials stems from their high availability, rapid reproduction, low environmental footprint, and the potential to replace conventional, non-biodegradable polymers used in packaging, biomedical, and agricultural applications. The extraction of biopolymers from Orthoptera typically involves chemical, biological, or combined (eco-friendly) approaches. Different extraction methods affect not only the intrinsic properties of the biopolymers but also their biomaterial-forming capacity. Overall, understanding and optimizing the extraction processes from Orthoptera sources are crucial for the large-scale valorization of insect biomass into eco-friendly biopolymers. These advances contribute significantly to the circular bioeconomy and the development of biodegradable materials for diverse industrial applications.

3.1. Extraction of proteins

Edible insects are a great source of protein, with crickets having between 55 % and 70.75 % of protein (González et al., 2019; Rumpold & Schlüter, 2013). Different extraction methods significantly impact both the yield and quality of proteins obtained from Orthopterans (Table 1). The Protein Recovery Yield (PRY), functionality and bioavailability can be enhanced by the application of pre-treatments, selection of appropriate solvents, and advanced extraction technologies (Amarender et al.,

2020; Cruz-López et al., 2024; Ndiritu et al., 2017; Psarianos, Dimopoulos, et al., 2022; Vandeweyer et al., 2017). Among the various methods used for isolating protein fractions from crickets, the most applied in literature involves drying (freeze or oven drying), followed by defatting (to remove lipid contents), and then performing alkaline extraction (Gravel & Doyen, 2020). Afterward, the mixture is centrifuged, yielding a supernatant containing soluble proteins and a precipitate containing insoluble fractions, such as chitin and fibers (Gravel & Doyen, 2020; Pellerin & Doyen, 2024). This method has the advantage of increasing the insect protein's solubility at alkaline pH, resulting in high levels of recovery (Pan et al., 2022; Purkiewicz et al., 2025). Moreover, an additional precipitation process can be applied to the supernatant by adjusting the pH to around 4–5 in order to obtain solid protein pellets (Cunha et al., 2025).

Although alkaline extraction is widely used due to its efficiency, acid extraction methods have also been explored as viable alternatives. In this case, the protein is typically recovered from the precipitate (pellet), while the supernatant is discarded (Cunha et al., 2025, p. 1164). Amarender et al. (2020) reported higher PRY for acid extractions, with 82.95 % using ascorbic acid, compared to only 67.66 % obtained with alkaline sodium hydroxide (NaOH) solutions. In contrast, Cunha et al. (2025), p. 1164 obtained protein yields of 46.34 % and 60.44 % for acid and alkaline extractions, respectively. These differences may be attributed to the type and condition of the raw material. Amarender et al. (2020) have used commercial spray-dried powder, while Cunha et al. (2025), p. 1164 have used oven-dried crickets at 140 °C. This high-temperature exposure appears to promote protein denaturation, potentially reducing extraction applicability. Lower protein recoveries, with a reduction from 36 % to 72 %, have also been observed after blanching crickets at 100 °C (Pellerin & Doyen, 2024).

The defatting of cricket samples improves the PRY; however, the choice of methodology and solvent is crucial. Although hexane is considered neurotoxic (Cunha et al., 2025, p. 1164), Pellerin and Doyen (2024) reported that it slightly increased protein recovery from house crickets (*A. domesticus*) compared to the control (~85 %), reaching 86.9 % with Soxhlet and 85.9 % with maceration. In contrast, the use of ethanol, especially when heated, seems to desaturate proteins, resulting in significantly lower yields of 23.2 % and 74 %, respectively. While methyl-tert-butyl-ether also showed promising results, other solvents

Table 1
Different methodologies to extract protein from Orthopteran.

Pre-treatments	Drying	Defatting	Extraction Method	Extraction Solvent	PRY (%)	References
n/a	Freeze-drying	Hexane	Blanching	Ascorbic Acid	48.32–66.35	Ndiritu et al. (2017)
n/a	Spray-Drying	Ethanol	Maceration	NaOH (0.5 M)	82.95	Amarender et al. (2020)
n/a	Oven Drying	Ethanol	Maceration	Ascorbic Acid	67.66	Cunha et al. (2025)
				NaOH (0.5 M)	60.44	
				Ascorbic Acid (0.5 M)	46.34	
				Enzymes (Alcalase)	69.91	Eze et al. (2025)
Blanching	Oven Drying	Supercritical CO ₂ /Petroleum ether	Maceration	NaOH (2 M)	69.77–73.93	
				Natural deep eutectic solvent		
				Sodium chloride (0.8 M)		
Pulsed electric fields (PEF)	Freeze-drying	Hexane	Maceration	NaOH (0.5 M)	72.45	Psarianos, Ojha, et al. (2022)
n/a	Freeze-drying	Hexane	Maceration	NaOH (1 M or 4 M)	65.87	Purschke et al. (2018)
n/a	Frozen in liquid nitrogen	Distilled water	Maceration	HCl (2 M)/NaOH (2 M)	48.5–77.9	Mishyna et al. (2024)
n/a	Freeze-drying	Hexane	Maceration	NaOH (2 M)	45.75	Quinteros et al. (2022)
Blanching	Freeze-drying	n/a	Maceration	NaOH (1 M)	27.7	
		Hexane			24.1	Pellerin and Doyen (2024)
		Ethanol			14.8	
		n/a			85.5	
n/a	Freeze-drying	Hexane	Maceration	NaOH (1 M)	86.9	Cruz-López et al. (2024)
		Ethanol			23.2	
		Hexane			41.94	
n/a	Dehydrated	Hexane	Ultrasound-Assisted Maceration	NaOH (0.5 M)	11.29	

such as chloroform, chloroform: methanol, and hexane: isopropanol reduced protein yields to levels below the non-defatted samples, highlighting their negative effect on extraction efficiency (Rose et al., 2023). Moreover, defatting the cricket meal with the supercritical CO₂ proved to be more prominent, providing higher protein content than its petroleum ether-treated counterpart (Eze et al., 2025).

The application of the emerging techniques, such as pulsed electric fields and ultrasound-assisted extraction, proved to act directly on cellular membranes, enhancing protein extraction yield. Pulsed electric fields represent a valuable pre-treatment for crickets, which promote electroporation and increase membrane permeability. Psarianos, Ojha, et al. (2022) reported that the application of pulsed electric fields with 4.90 kJ/kg as a pre-treatment increased the protein extraction yield by 18 %. Furthermore, the use of ultrasonic frequency during alkaline

extraction improved total protein content, digestibility, and overall recovery when compared to conventional maceration techniques (Cruz-López et al., 2024). The use of enzymes for protein extraction results in higher recovery yields, as the enzymes increase the degree of hydrolysis and liberate free amino acids (Sungsi-In et al., 2024). Cunha et al. (2025), p. 1164 reported that the alcalase (a protease from *Bacillus licheniformis*) displayed a higher protein extraction yield than traditional acid or alkaline solvents, providing an improved solubility and reduced fiber content.

3.2. Extraction of chitin and chitosan

Chitin and its derivative chitosan have several applications in medicine, cosmetics and food applications (El Knidri et al., 2018). Chitin is

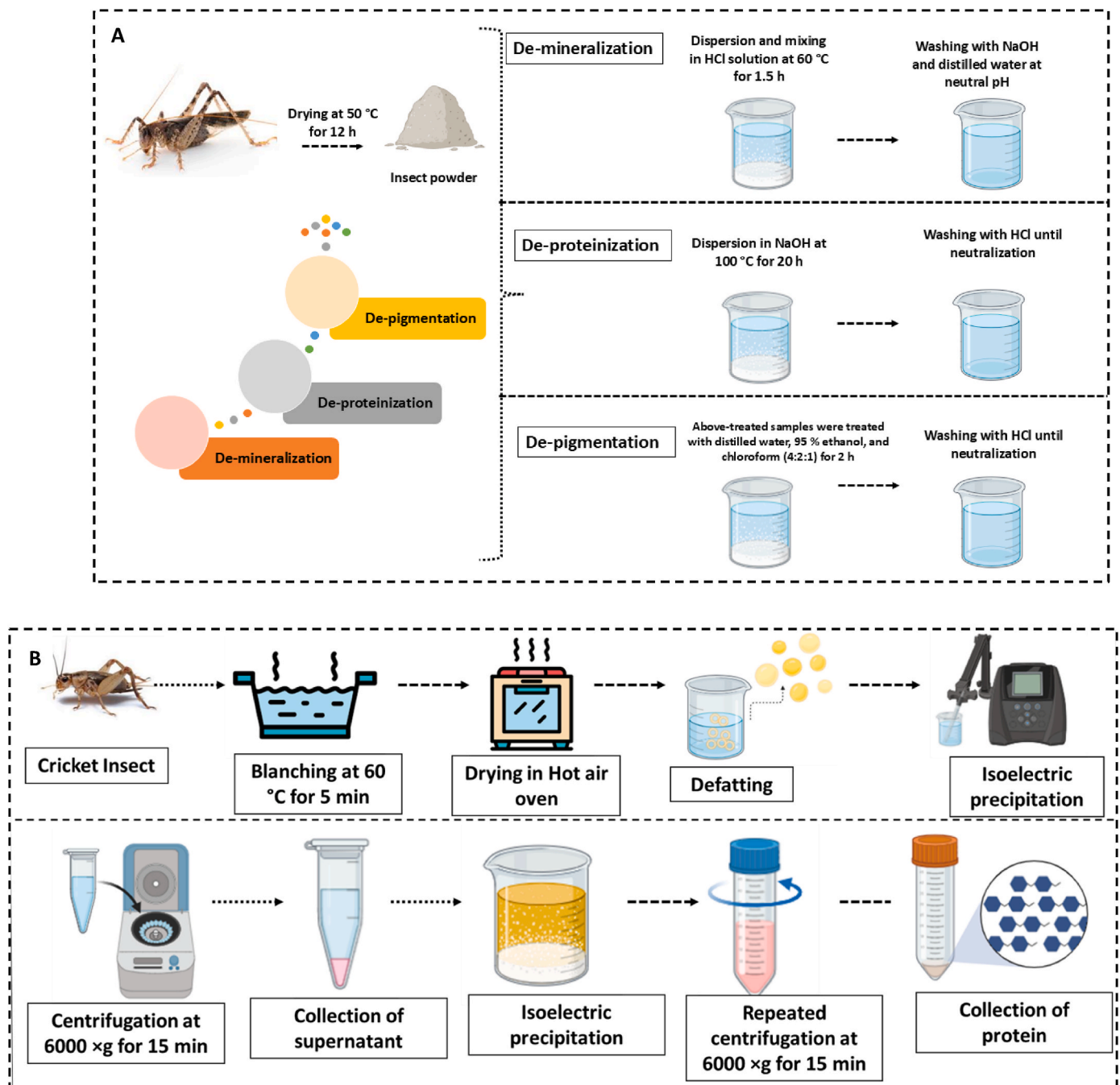


Fig. 2. Extraction procedure steps of chitosan (A) and protein using isoelectric precipitation (B) from crickets.

insoluble in the common solvents, while chitosan is soluble in most aqueous acidic solutions, making it a more versatile material for a wide range of industrial and functional applications (Rinaudo, 2006; Roy et al., 2017). The main distinction between chitin and chitosan is observed in the degree of N-acetyl amino groups, which influences their chemical structure and functional properties (Fig. 2). When the acetylation degree exceeds 50 %, the polymer is classified as chitin; inversely, when it is below 50 %, it is referred to as chitosan (El Knidri et al., 2018; Gonil & Sajomsang, 2012). The deacetylation process is, therefore, a crucial step in converting chitin into chitosan, as it influences its reactivity and potential applications (Roy et al., 2017).

The extraction of chitin from crickets demands a demineralization step to remove the mineral content, mainly calcium carbonate (CaCO_3) and calcium chloride (CaCl_2), followed by a deproteinization step to eliminate proteins associated with the exoskeleton (El Knidri et al., 2018; Espinosa-Solis et al., 2024). Performing demineralization prior to deproteinization seems to enhance both the final chitin yield and the efficiency of the deproteinization process (Aytekin & Elibol, 2010). The demineralization is performed with the acid treatment, mostly using hydrochloric acid (HCl) solution, while the deproteinization and deacetylation are performed in an alkaline medium using NaOH solutions (Hamed et al., 2016). The age of crickets also has a significant impact on chitin extraction content, increasing from 2.20 g/100 g in 4-week-old crickets to 12.40 g/100 g in 13-week-old crickets (Carolynne et al., 2017).

NaOH concentration can significantly impact the deacetylation process. The use of NaOH 50 % (w/v) seems to result in degrees of deacetylation below 20 %, which does not qualify the product as chitosan. In contrast, applying NaOH 50 % (w/w) under the same conditions resulted in deacetylation levels exceeding 90 % (Kim et al., 2017). Espinosa-Solis et al. (2024) optimized the crickets' chitin purification processes by using Box-Behnken response surface methodology. Although the demineralization results were similar for different parameters, the conditions of 30 °C/2M HCl solution/3 h resulted in comparable efficiency with the lowest time and temperature. For deproteinization, the optimal conditions included a temperature of 80 °C, a reaction time of 45 min, and a NaOH concentration of 2 M. Demineralization and deproteinization yielded 92.25 ± 0.67 % and 43.23 ± 1.25 %, respectively. Similar demineralization results were obtained with 98 °C/1M HCl solution/2 h (91.1 ± 0.3 %) (Psarianos, Ojha, et al., 2022). However, the relationship between deproteinization and/or demineralization efficiency and chitin yield is not necessarily linear, and those conditions can negatively affect the quantity and quality of the extracted polymer.

The application of microwave treatment as a pre-drying step before the extraction of chitin and chitosan from crickets improved chitin yield and reduced residual protein content (Yuan et al., 2025). In contrast, the use of microwave treatment during chemical deproteinization and demineralization led to similar chitosan yields compared with proteases, fermentation and conventional methods (Psarianos et al., 2025). Besides, the application of the microwave technique reduced the processing time from 26 h to 16 min; however, the obtained chitosan presented lower solubility (Psarianos et al., 2025). Psarianos, Dimopoulos, et al. (2022) investigated the effect of pulsed electric fields as a pretreatment on chitin extraction from cricket flour (*A. domesticus*) and reported an increase in fat and protein extraction yields by 40 % and 18 %, respectively; however, no significant impact on chitin yield was found. Ibitoye et al. (2018) employed a 1M NaOH solution at 95 °C to deproteinize *B. portentosus* cricket samples for 6h, followed by demineralization in oxalic acid (1 g/100 ml) at room temperature for 3h. A subsequent decolorization step was performed using a 1 % sodium solution at room temperature for 3h to obtain chitin with reduced pigment content and improved applicability. Chitosan was then produced via deacetylation using a 50 % NaOH solution at 121 °C for 5 h. The resulting yields were 7.10 g of chitin and 5.80 g of chitosan per 100 g of dry weight, respectively.

Biological extraction methods for chitin and chitosan from Orthoptera have been explored due to the environmental impact of the chemical methods (El Knidri et al., 2018). Among many biological methods, enzyme-assisted and microbial fermentation have gained particular attention as they yield products with higher-quality products and cause less damage to the environment (Psarianos, Ojha, et al., 2022; Xiong et al., 2023). Psarianos, Ojha, et al. (2022) investigated green approaches for chitin extraction and its conversion into chitosan. While the conventional chemical chitosan purification method yielded 81.9 mg/100 mg d.w., the combination of enzymatic (bromelain) deproteinization and biological fermentation (lactic acid) demineralization achieved a higher yield of 88 mg/100 mg d.w., with similar degrees of deacetylation between methods. However, the fermentation demineralization process required 7 days, whereas the HCl chemical method was completed in 2 h. In another study, a green approach was used for chitin using deep eutectic solvents or fermentation (*B. subtilis*) (Psarianos, Ojha, et al., 2022). It resulted that the extraction using deep eutectic solvents required 6 h and the fermentation (lactic acid)-based extraction was performed in five days, giving chitin yield of 6.00–13.00 mg/100 mg d.w., while the conventional alkaline extraction with NaOH achieved 27.10 mg/100 mg d.w. in 28 h (Psarianos, Ojha, et al., 2022).

Although insects yield less chitin per kg of dry biomass, their extraction process is simpler, faster, and requires fewer harsh chemicals, which reduces processing cost and environmental treatment expenses. Indeed, the insect biomass often has low mineral content (so the demineralization step can be skipped or simplified), easing extraction (Mersmann et al., 2025). While the crustacean shell waste requires both demineralization (using strong acids) and deproteinization (using strong alkali), which are "hazardous, energy-consuming and environmentally unfriendly (Arbia et al., 2013). Additionally, insect farming is generally more cost-effective due to its lower resource demands and quicker growth rates, which further decrease overall production costs (Izadi et al., 2025).

4. Formulation of biomaterials from orthoptera-based biopolymers

Recent advances in sustainable food packaging have increasingly focused on the search for alternative sources of biopolymers, such as crickets and grasshoppers. While the use of Orthoptera-based biopolymers has been explored to some extent, their application in the production of biomaterials remains relatively recent. To date, only a limited number of studies have focused on the production of biomaterials from Orthoptera-based biopolymers, underlining their significant and promising ability to advance sustainable biopackaging technologies (Table 2).

4.1. Orthoptera chitosan-based biomaterials

The packaging potential of chitosan extracted from *A. domesticus* and *G. sigillatus* was successfully tested by producing films for food application (Malm et al., 2021). The films were formulated by combining cricket-based chitosan solutions (1 % w/v) prepared in acetic acid (1 % (v/v)) with glycerol (37.5 % of chitosan weight) used as a plasticizer (Malm et al., 2021). The film solutions were cast into Petri disks, left to dry for 24h at 50 °C and the resulting films were found to be as effective as commercial shrimp chitosan films while providing additional advantages such as good mechanical properties, barrier properties, improved water resistance and increased light barrier characteristics (Malm et al., 2021). These results are in agreement with the previous study, which reported that the cricket-derived chitosan showed comparable or superior bioactivity and film-forming behavior, often with different molecular weight and crystallinity than crustacean chitosan (Chae et al., 2018), making it promising for specialty biomaterials and packaging, while crustacean chitosan remains the economical industrial baseline.

Table 2
Orthoptera-based biopolymers for the preparation of packaging materials.

Species of Orthoptera	Biopolymers extracted and used	Film/nanoparticle preparation methods	Film formation methods	References
<i>Acheta domesticus</i> and <i>Gryllosid sigillatus</i>	Chitosan	1 % w/v of chitosan dissolved in 1 % acetic acid (v/v) solution + 37.5 % glycerol (w/w chitosan) + Homogenization	Casting + drying for 36 h at 50 °C	Malm et al. (2021)
<i>Acheta domesticus</i>	Chitosan	Chitosan and polysorbate-80 dissolved in 75 mL of a 0.2 % v/v acetic acid solution + Homogenization + Aqueous solution of sodium citrate as crosslinker + Homogenization	–	Inthorn et al. (2024)
<i>Locusta migratoria</i>	Protein	Locust protein (6 %, 7 %, 8 %) dissolved in deionized water + glycerol (35 %, 40 %, 45 % (w/w) of protein powders) + Homogenization + Heating-Stirring (80 °C for 40 min at 600 rpm)	Casting + air-drying oven for 48 h at 50 °C	Zhang et al. (2022)
<i>Locusta migratoria</i>	Protein	0.6 g (w/v) of locust protein + 0.9 g (w/v) of carrageenan (40:60) in distilled water + glycerol was added (14 %, w/v) + <i>E. purpurea</i> nanoparticles (1.0 %, 1.5 % and 2.0 %) + Homogenization + Heating-Stirring	Casting + air-drying oven (5 h at 55 °C)	Singh et al. (2023)
<i>Acheta domesticus</i>	Protein	0.6 g (w/v) of cricket protein + 0.9 g (w/v) of carrageenan (40:60) in distilled water + glycerol was added (14 %, w/v) + Homogenization + Heating-Stirring	Casting + air-drying oven (5 h at 55 °C)	Lone, Bhat, et al. (2025)
<i>Locusta migratoria</i>	Protein	0.6 g (w/v) of locust protein + 0.9 g (w/v) of carrageenan in distilled water + glycerol (14 %, w/v) as a plasticizer + <i>E. Purpurea</i> -based nanoparticles (0.0, 1.0, 1.5, and 2.0 %, w/v) in glycerol + Homogenization + Heating-Stirring	Casting + air-drying oven (5 h at 55 °C)	Singh et al. (2024)
<i>Acheta domesticus</i>	Protein	0.75 g (w/v) of cricket protein + 0.75 g (w/v) of carrageenan in distilled water (100 mL) + 14 mL of glycerol + <i>A. paniculata</i> leaf extract-based nanoparticles (0.5, 1.0 and 1.5 %) + Homogenization + Heating-Stirring	Casting + air-drying oven (6 h at 55 °C)	Lone, Kumar, et al. (2025)

In another study, chitosan was isolated from *A. domesticus* and investigated for developing nanoparticles useable as sources of cosmeceutical delivery systems (Inthorn et al., 2024). The cricket chitosan-based nanoparticles were prepared by dissolving the extracted chitosan and polysorbate-80 in 75 mL of a 0.2 % v/v acetic acid solution and homogenized. The aqueous solution of sodium citrate was added to the chitosan solution as a crosslinking agent and the mixture was homogenized (Inthorn et al., 2024). It was found that the characteristics of cricket-based chitosan were similar to those of commercial chitosan, except that the cricket-based chitosan displayed a higher crystallinity and a lower molecular weight. Moreover, the cricket-derived chitosan showed potential for a range of applications, including the use as a nanocosmeceutical delivery system in topical and cosmetic formulations.

4.2. Orthoptera protein-based biomaterials

The use of Orthoptera protein has garnered great attention for its application in the food sector; however, minimal studies have investigated its potential for the development of a sustainable packaging system. Zhang et al. (2022) formulated films with food packaging potential using protein extracted from *L. migratoria*. The films were conceived by dissolving the locust protein in deionized water to reach concentrations of 6 %, 7 % and 8 %. Afterward, different amounts of glycerol as a plasticizer were added, making it 35 %, 40 %, and 45 % (w/w) of cricket protein. The film solutions were heat-stirred at 80 °C for 40 min at 600 rpm, cast into PTFE molds and oven at 50 °C for 48 h (Zhang et al., 2022). In another study conducted in 2023, *L. migratoria* protein and *E. purpurea* flower extract-based nanoparticles were used to prepare bioactive edible films with the potential to stabilize food products (Singh et al., 2023). These novel Orthoptera protein-based edible bioactive films were obtained by firstly dissolving the 0.6 g of locust protein and 0.9 g of carrageenan in distilled water, followed by the addition of 14 % of glycerol and 1.0 %, 1.5 % and 2.0 % of *E. purpurea* flower extract-based nanoparticles. The film solutions were poured on flat glass plates and hot-air oven-dried, resulting in protein-based edible bioactive films (Singh et al., 2023). Singh et al. (2024) proposed bioactive edible films from the protein extracted from *L. migratoria*. For this purpose, on one hand, insect protein (0.6 g) and carrageenan (0.9 g) at 60:40 (w/w) were dissolved in distilled water (100 mL) and 14 % of glycerol was added as a plasticizer. The film solution was enriched with *E. purpurea*-based nanoparticles (0.0, 1.0, 1.5, and 2.0 %, w/v) dissolved in glycerol, homogenized, cast on flat glass plates and air-oven dried (Singh et al., 2024). Similarly, protein extracted from *A. domesticus*

crickets has been investigated for the development of edible film (Lone, Bhat, et al., 2025). For the preparation of the film, *A. domesticus* cricket protein (0.6 g) was combined with carrageenan (0.9 g) at 60:40 (w/w) in distilled water (100 ml), left to dissolve and 14 % glycerol was added as a plasticizer. The film solution was homogenized, cast into glass plates and dried in an air-drying oven at 55 °C for 5 h (Lone, Bhat, et al., 2025). In a recent work, *A. domesticus* cricket protein-based edible active films were successfully designed by combining cricket protein, carrageenan and nanoparticles formed from *A. paniculata* leaf extract (Lone, Kumar, et al., 2025). The composite films were formed by associating cricket protein (0.75 g), carrageenan (0.75 g), glycerol (14 mL) and *A. paniculata* leaf extract-based nanoparticles (0.5 %, 1.0 % and 1.5 % w/v). The uniform layered films were developed by pouring uniform layers of the filmogenic solutions (60 °C) on glass plates, which were dried in an air-drying oven for 6 h at 55 °C (Lone, Kumar, et al., 2025). Orthoptera protein-based films exhibit not only good mechanical and barrier performance but antioxidant activity, antimicrobial effects, biodegradability and edibility abilities, ensuring environmental safety and food compatibility.

5. Characterization of orthoptera-based biopolymers

The growing interest in the global food packaging market is advantageous for the development of research, innovation, and circular economy applications in packaging technologies. However, all the quality parameters of packaging materials should be efficiently taken into account. The evaluation of film characteristics is crucial for providing the numerical data necessary for an objective assessment of the film's degree of excellence and determining whether it is suitable for food packaging (Weng et al., 2023). Film characteristics such as optical properties, color, water-holding capacity, solubility, mechanical strength and bioactive properties are measured to define the performance and the ability of food packaging (Malm et al., 2021; Weng et al., 2023). The characteristics of Orthoptera biopolymer-based food packaging materials are summarized in Table 3.

5.1. Optical and color properties

The optical and color properties of food packaging are determinant factors for the appearance and acceptance of food packaging materials. Malm et al. (2021) compared the optical and color properties of the films from chitosan extracted from *A. domesticus* and *G. sigillatus* with the commercial shrimp chitosan film. Although Orthoptera chitosan films were bright, they were darker, less green and more yellow than shrimp

Table 3
Characteristics of biomaterials made from Orthoptera-based biopolymers.

Species of Orthoptera	Type of biomaterial	Biopolymers extracted	Opacity (mm ⁻¹)	L*	a*	b*	Density (g/mL)	Thickness (mm)	Water vapor permeability (g/m ² ·s·Pa)	Contact Angle (°)	Tensile stress (MPa)	Elongation at break (%)	Bioactive properties	References
<i>Acheta domesticus</i>	Film	chitosan	1.50–1.6	70.60–74.71	-0.02–1.44	24.64–30.16	-	-	2.09·10 ⁻¹⁰ -2.29·10 ⁻¹⁰	101	19–26.00	39–48	-	Malm et al. (2021)
<i>Grylodes sigillatus</i>	Film	Chitosan	1.60–1.70	69.90–72.23	1.23–1.86	23.65–26.40	-	-	2.34·10 ⁻¹⁰ 2.43·10 ⁻¹⁰	102	16.00–27.50	42–64	-	-
<i>Acheta domesticus</i>	Film	Protein	-	68.80–74.40	0.81–0.87	3.11–3.56	0.83–0.89	0.147–0.148	-	-	-	47.60–48.25	Antioxidant and antimicrobial activities	Lone, Bhat, et al. (2025)
<i>Acheta domesticus</i>	Film	Protein	-	73.78–78.22	0.93–0.97	3.19–3.54	1.01–1.06	0.143–0.145	-	-	-	52.80–52.80	Antioxidant and antimicrobial activities	Lone, Bhat, et al. (2025)
<i>Locusta migratoria</i>	Film	Protein	-	71.00–76.50	1.00	4.10–5.00	1.00–1.20	0.082–0.09	-	-	-	50.00–52.50	Antioxidant and antimicrobial properties	Singh et al. (2024)
<i>Locusta migratoria</i>	Film	Protein	-	71.00–77.00	1.00	4.200–5.200	1.00–1.20	0.082–0.09	-	-	-	50.00–52.50	Antioxidant and antimicrobial properties	Singh et al. (2023)
<i>Locusta migratoria</i>	Film	Protein	-	10.265–12.305	(-0.171)-(-0.043)	(-1.055)-(-0.372)	-	0.376–0.472	1.379 × 10 ⁻¹⁰ -2.267 × 10 ⁻¹⁰	27.50–48.00	-	3.95–23.15	-	Zhang et al. (2022)

films. L*, a* and b* values were 70.60–74.71, -0.02–1.44 and 24.64–30.16 for *A. domesticus* and 69.90–72.23, 1.23–1.86 and 23.65–26.40 for *G. sigillatus*, respectively (Malm et al., 2021). *Acheta domesticus* protein-based films exhibited a combination of lightness, redness, and yellowness (Lone, Bhat, et al., 2025; Lone, Kumar, et al., 2025). Similarly, *L. migratoria* protein-based films presented a combination of lightness, redness and yellowness (Singh et al., 2023, 2024). However, the incorporation of plant-based nanoparticles significantly affects the optical and color properties of Orthoptera biopolymer-based biomaterials. Furthermore, Zhang et al. (2022) reported that an increase in the amount of *L. migratoria* protein in the film formation showed a decrease in the L* value, indicating that the film became darker.

5.2. Density and thickness

The density and thickness of food packaging materials are among the most important parameters that affect their performance. The best density of food packaging materials to perform efficiently is related to the type of food, the shelf-life requirements and the function of the packaging. The density of *A. domesticus* protein-based film enriched with *Caralluma fimbriata* extract-based nanoparticles was 0.83–0.89 g/mL (Lone, Bhat, et al., 2025), while slightly higher range density of 1.01–1.06 g/mL was reported in *A. domesticus* protein-based film enriched with *Andrographis paniculata* leaf extract-based nanoparticles (Lone, Kumar, et al., 2025). Similarly (Singh et al., 2023), and Singh et al. (2024) reported a range of density of 1.00–1.20 g/mL for *L. migratoria* protein-based film enriched with *E. purpurea* flower extract-based nanoparticles. The increase in the film density can improve the tensile strength and strain at break which are determinants for the film quality and efficiency for the application in food packaging (Lavrić et al., 2021; Nilsen-Nygaard et al., 2021).

Nilsen-Nygaard et al. (2021) emphasized that particular attention has been driven to the optimization of the packaging process for improved efficiency and reducing the thickness of materials. Although a wide variety of thicknesses has been reported based on the polymer used in each work, some film quality parameters are related to the thickness. Guzman-Puyol et al. (2022) mentioned that all transparency measurements (transmittance included) are highly dependent on the thickness. In addition, it has been remarked that the water vapor permeability of films is related to the film thicknesses (Kokoszka et al., 2010; Zhang et al., 2022). *A. domesticus* protein-based film enriched with *Caralluma fimbriata* extract-based nanoparticles displayed a range of thickness of 0.147–0.148 mm (Lone, Bhat, et al., 2025). Likewise, a range value of 0.143–0.145 mm was found for *A. domesticus* protein-based film enriched with *Andrographis paniculata* leaf extract-based nanoparticles (Lone, Kumar, et al., 2025). However, films with a lower thickness (about 0.09 mm) were obtained from *L. migratoria* protein-based film enriched with *E. purpurea* flower extract-based nanoparticles (Singh et al., 2023, 2024). The increase in *L. migratoria* protein concentration from 6 % to 8 % in film formation occurred the increase of film thickness from 0.376 mm to 0.443 mm (Zhang et al., 2022). Moreover, the effect of glycerol on film thickness was similar to protein concentration, as the glycerol concentration increased from 35 % to 45 %, the film thickness increased to 0.471 mm (Zhang et al., 2022).

5.3. Water vapor permeability

The water vapor permeability is an important parameter when evaluating food packaging materials since it provides information on the barrier ability of packaging materials to water. The ability of food packaging materials to decrease water vapor migration is an important property for their application (Malm et al., 2021). *A. domesticus* chitosan-based films displayed a range of water vapor permeability of 2.09·10⁻¹⁰–2.29·10⁻¹⁰ g/m·s·Pa, while higher values of 2.34·10⁻¹⁰–2.43·10⁻¹⁰ g/m·s·Pa were obtained for *G. sigillatus* chitosan-based films (Malm et al., 2021). In the same study, it was found

that the films derived from cricket chitosan had lower water vapor permeability compared with shrimp chitosan film (Malm et al., 2021). In another study, it was shown that the water vapor permeability of *L. migratoria* protein-based film increased from 1.379×10^{-10} g/m·s·Pa to 2.267×10^{-10} g/m·s·Pa as the protein content increased from 6 % to 8 % (Zhang et al., 2022). This trend was attributed to film thickness and glycerol content (Kokoszka et al., 2010; Shaw et al., 2002; Zhang et al., 2022).

The water vapor transmission rate of 1.84–1.91 mg/m² was reported for *A. domesticus* protein-based film enriched with *C. fimbriata* extract-based nanoparticles (Lone, Bhat, et al., 2025). In another work, the water vapor transmission rate of 2.01–2.09 mg/m² was reported for *A. domesticus* protein-based film enriched with *A. paniculata* leaf extract-based nanoparticles (Lone, Kumar, et al., 2025). It was figured out that the presence of the plant extract-based nanoparticles caused a significant decrease in the water vapor transmission rate, they impede the free interaction of water molecules with binding sites in the film matrix and reduce the water vapor transmission rate (Lone, Bhat, et al., 2025; Lone, Kumar, et al., 2025). Moreover, *L. migratoria* protein and *E. purpurea* nanoparticles-based films had water vapor transmission rates ranging from 2.00 to 2.10 mg/m² (Singh et al., 2023, 2024). It was affirmed that a decrease in water vapor transmission rate of films is a favorable change that can reduce the loss of moisture from the product and retain the product quality during storage (Singh et al., 2023, 2024).

5.4. Contact angle

The contact angle of food packaging materials measures their wettability by a given angle at which a liquid interface meets the material surface. The water contact angle is considered as the most convenient method of analyzing the hydrophilic/hydrophobic properties of packaging material surfaces (Šćetar et al., 2017). As the contact angle increases, the potential for the two to interact decreases (Meiron & Saguy, 2007). In a previous study, the contact angles of *A. domesticus* chitosan film, *G. sigillatus* chitosan film and commercial shrimp chitosan film were found as 101°, 102° and 93°, respectively (Malm et al., 2021). These results revealed that cricket chitosan-based films are more hydrophobic than commercial chitosan films, suggesting that cricket chitosan has an advantage for biobased food packaging compared to traditional crustacean chitosan. In another study, the contact angle of *L. migratoria* protein-based films was found in the range of 27.50–48.00°, evidencing that these locust protein-based films had hydrophilic surfaces (Zhang et al., 2022). However, the increase of protein content in the films improved the hydrophobicity of the surface by augmenting the water contact angle. In contrast, the increase in glycerol content from 35 % to 45 % resulted in a decrease in the hydrophobicity of the surface, reducing the water contact angle from 45.90° to 38.60° (Zhang et al., 2022). It was explained that on the one hand, glycerol tends to decrease the surface tension of the film, favoring the wettability of the film surface, and on the other hand the increased polypeptide chain mobility could facilitate the water absorption and transport within the film (Kokoszka et al., 2010). Moreover, the variation of the pH from 9 to 11 resulted in a decrease in the water contact angle of Orthoptera protein-based films from 49.4° to 42.7° mainly due to the change that the pH variation in the structure of films (Zhang et al., 2022).

5.5. Tensile strength and elongation at break

The tensile strength of packaging materials is a mechanical property that measures the withstanding capacity of the materials while being stretched or pulled before breaking. The tensile strength is a critical property for packaging materials since it affects their durability, load-carrying capacity, and resistance to tearing. The mechanical properties, such as tensile strength, depend on film composition, crosslinking and environmental conditions (Yin et al., 2023). The tensile strength of *A. domesticus* and *G. sigillatus* chitosan films varied from 19 MPa to

26.00 MPa and from 16.00 MPa to 27.50 MPa, respectively (Malm et al., 2021). It was found that the cricket chitosan films had similar or greater tensile strength than the commercial shrimp chitosan film, suggesting a good intramolecular bonding between cricket chitosan (Malm et al., 2021). Nonetheless, Zhang et al. (2022) reported lower tensile strengths of 1.03–2.99 MPa for *L. migratoria* protein-based films. They reported that the content of glycerol from 30 to 50 % was the best range for film forming of locust protein and it is difficult to obtain a complete film when the glycerol content is lower than 30 % while the glycerol content is greater than 50 % resulting in a too viscous to demould film (Zhang et al., 2022).

Elongation at break is a mechanical property that shows how much a packaging material can stretch before it breaks. About 39–48 % and 42–64 % of elongation at break were reported *A. domesticus* and *G. sigillatus* chitosan films (Malm et al., 2021). Similarly, a range of elongation at break of 47.60–48.25 % was reported for *A. domesticus* protein-based films containing *C. fimbriata* extract-based nanoparticles (Lone, Bhat, et al., 2025). Likewise, Lone, Kumar, et al. (2025) reported an elongation of 52.80–52.80 % for *Acheta domesticus* protein-based composite film containing *Andrographis paniculata* leaf extract-based nanoparticles. In addition, *L. migratoria* protein-based films displayed a range of elongation at break of 50.00–52.50 % (Singh et al., 2023, 2024), which is consistent with that reported for *A. domesticus* protein or chitosan-based films. Nonetheless, Zhang et al. (2022) reported low elongation at break of 3.95–23.15 % for *L. migratoria* protein-based films. These findings suggest that elongation at break of a film is intrinsically related to the components forming the film.

5.6. Bioactive properties

A. domesticus protein-based film displayed 0.82 g GAE/mg of total phenolic content, 1.02 µg QE/mg of total flavonoid content, 1.24 % inhibition of DPPH radical scavenging, 2.23 % inhibition of ABTS radical scavenging and 0.88 µM TE/100 g of ferric iron reducing power (Lone, Bhat, et al., 2025). The addition of *C. fimbriata* extract-based nanoparticles (1.0–3.0 %) to *A. domesticus* protein for the film formation showed a significant increase in the total phenolic and total flavonoid contents of *A. domesticus* protein-based film, resulting in a significant increase in antioxidant potential of *A. domesticus* protein-based film (Lone, Bhat, et al., 2025). In another study, the total phenolic content, total flavonoid content, DPPH radical scavenging, ABTS radical scavenging and ferric iron reducing power of *A. domesticus* protein-based film were determined as 0.86 µg GAE/mg, 1.12 µg QE/mg, µg QE/mg, 1.42 % inhibition, 1.42 % inhibition and 0.98 µM TE/100 g, respectively (Lone, Kumar, et al., 2025). The incorporation of *A. paniculata* leaf extract-based nanoparticles to *A. domesticus* protein-based film resulted in an *A. domesticus* protein-based film and then an increase in the antioxidant potential (Lone, Kumar, et al., 2025). Similar tendencies were observed with *L. migratoria* protein-based films, where the antioxidant properties have increased with the incorporation of *E. purpurea* flower extract-based nanoparticles (Singh et al., 2023, 2024).

Acheta domesticus protein-based film showed good antimicrobial properties against *E. coli* and *S. aureus*, displaying the zones of inhibition of 9.50–14.45 mm and 11.00–14.54 mm, respectively (Lone, Bhat, et al., 2025; Lone, Kumar, et al., 2025). This antimicrobial potential of the *A. domesticus* protein-based film might be attributed to *C. fimbriata* and *Andrographis paniculata* extract-based nanoparticles, which showed good antimicrobial properties (inhibitory halos and MIC) against *E. coli* and *S. aureus*. The inhibitory halos of the *A. domesticus* protein-based film showed a significant increase with the increasing concentration of *Caralluma fimbriata* or *Andrographis paniculata* extract-based nanoparticles against both *E. coli* and *S. aureus* (Lone, Bhat, et al., 2025; Lone, Kumar, et al., 2025). *L. migratoria* protein-based film displaying the zones of inhibition of 11.00–14.00 mm against *S. aureus*, showing a good antimicrobial activity against *S. aureus* (Singh et al., 2023, 2024).

Moreover, the addition of the *E. purpurea*-based nanoparticles enhanced the antimicrobial activities of the *L. migratoria* protein-based film and a significant increasing pattern was recorded for the size (mm) of inhibitory halos as the concentration of *E. purpurea*-based nanoparticles increased against *S. aureus* (Singh et al., 2023, 2024).

6. Application and biodegradability of orthoptera-based biopolymers

Recent developments in sustainable food packaging have

increasingly focused on the search for alternative sources to improve their functional and mechanical properties. While the extraction of Orthoptera-based biopolymers has been explored to some extent, their application in food packaging systems remains relatively novel. To date, few studies have explored the potential of Orthoptera-based biopolymers for designing innovative and sustainable food packaging materials (Fig. 3). Malm et al. (2021) acknowledged that edible Orthoptera chitosan has the potential to be used as bio-based packaging material for food and pharmaceutical applications. Nanoparticles developed from the chitosan extracted from *G. bimaculatus*, *Teleogryllus miratus* and

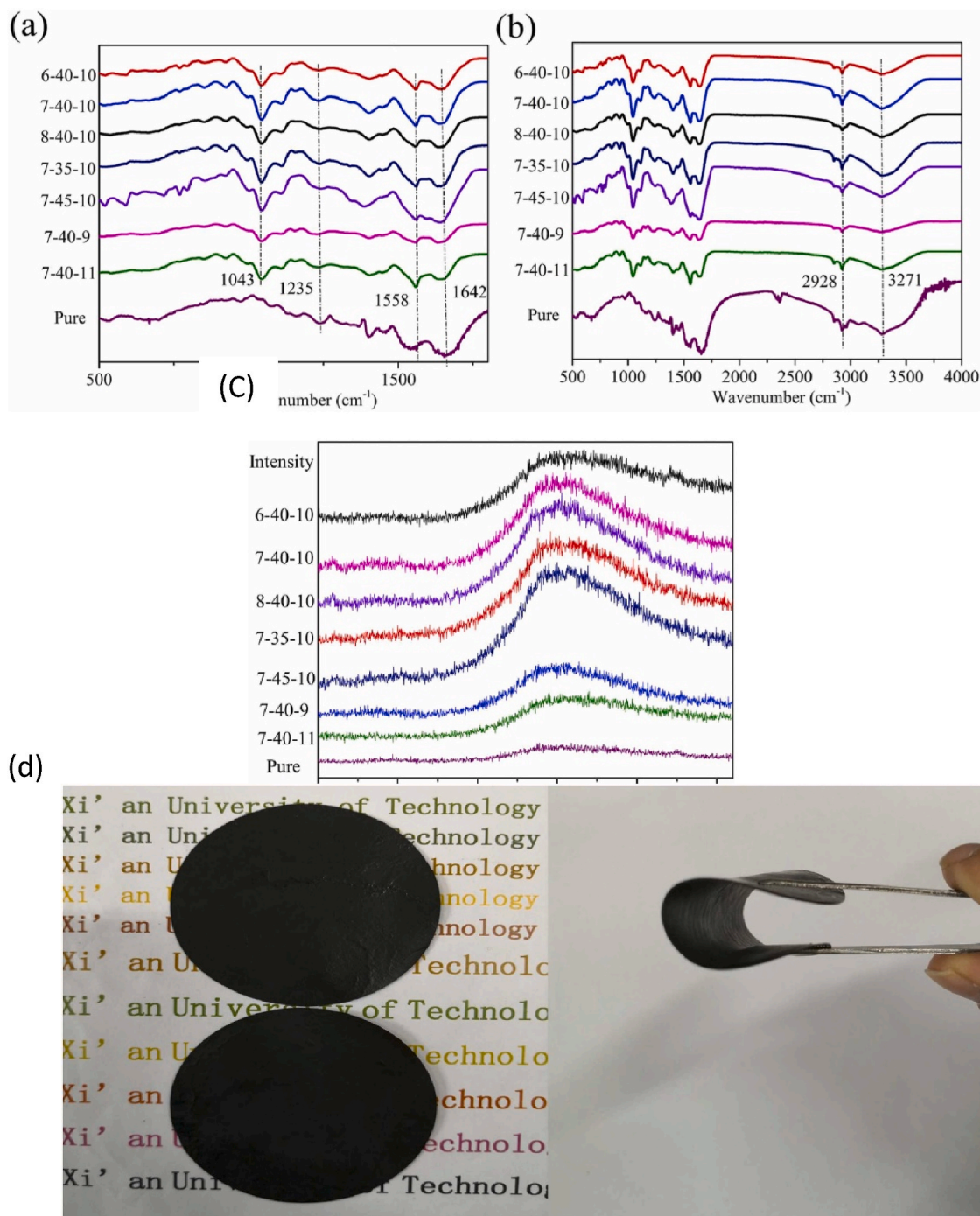


Fig. 3. Characterization of Locust protein-based edible films prepared using different concentrations of water, glycerol, and NaOH. (a) Fourier transform infrared spectroscopy (FTIR) at wavenumber 500-1800 cm^{-1} ; (b) Fourier transform infrared spectroscopy (FTIR) at wavenumber 500-4000 cm^{-1} ; (c) X-ray diffraction; (d) Pictorial representation of locust protein-based edible film. (Fig. 3 is adapted with the permission copyright © Elsevier Ltd, Amsterdam, the Netherlands, from Zhang et al., 2022).

A. domesticus displayed the potential as novel sources for cosmeceutical and nutraceutical delivery (Chae et al., 2018; Inthorn et al., 2024).

Similarly, Zhang et al. (2022) extracted protein from the locust insect and prepared the edible film. In their study, they used varied concentrations of glycerol (35–45 %) and protein (6–8 %) during the preparation of films at diverse pH levels ranging from 9 to 11. Moreover, different characterization techniques were used to characterize the films. For instance, XRD and FTIR data showed the excellent compatibilities between protein and plasticizer due to strong hydrogen bonding interactions as shown in Fig. 3a, b & c. Also, the pictorial representation of prepared films is illustrated in Fig. 4d. Singh et al. (2023) applied films formed from the composite *L. migratoria* protein, carrageenan and *E. purpurea* flower extract-based nanoparticles for the packaging of white chocolate. The packed samples were stored for 90 days and it showed that films enhanced the storage stability of chocolate during storage. The presence of *L. migratoria* protein-based films decreased the lipid and protein oxidation and increased the antioxidant, sensory and microbial qualities of the chocolate samples during storage. Furthermore, the gastrointestinal digestion simulation showed a positive effect on the antioxidant properties of the chocolate. Singh et al. (2024) used locust protein-based composite films developed with *L. migratoria* protein, carrageenan and *E. purpurea* extract-based nanoparticles for the packaging of parmesan cheese. The application of novel resulted in a positive impact on protein oxidation, lipid stability, microbial quality and antioxidant potential of parmesan cheese during a storage period of 90 days. In addition, the packaging with Orthoptera protein-based films displayed positive effects on the sensory characteristics of parmesan cheese and improved the antioxidant properties of *in vitro* digestion samples. Lone, Bhat, et al. (2025) investigated the packaging ability of bioactive films developed using cricket (*A. domesticus*) protein, carrageenan and *Caralluma fimbriata* extract-based nanoparticles. The application of the bioactive film for the packaging of cheddar cheese showed great advantages. Indeed, the application of *A. domesticus* protein-based films increased the antioxidant activities, lipid and protein oxidative stability, and microbial quality (microbial counts) of the cheddar cheese stored for 90 days. It was found that the sensory quality of cheddar cheese increased significantly. Moreover, the results of the gastrointestinal digestion simulation showed an augmentation of the antioxidant potential of cheddar cheese.

7. Health issues, consumer acceptance, legislation, and commercializability

The use of Orthoptera-derived biopolymers in biobased packaging materials is an area of potential market growth and offers a biodegradable alternative (Weng et al., 2023). However, despite its established use in the food sector, exploiting Orthopterans for these applications raises concern about toxin and heavy metal accumulation, as well as the possibility of allergic reactions. Additionally, their commercial feasibility is uncertain (Fernandez-Cassi et al., 2019; Lange & Nakamura, 2021; Ververis et al., 2022).

7.1. Health issues: Allergenic potential, toxins, and presence of heavy metals

House crickets are generally considered safe for their reported uses, as approved by the Commission Implementing Regulation (EU) No. 2022/188, and are now a permitted novel food ingredient (Siddiqui et al., 2024). However, experts point out that individuals with pre-existing sensitization to crustaceans, mites, and mollusks may experience allergic reactions (Lange & Nakamura, 2021; Turck et al., 2024). The concentration of contaminants depends on the presence of these substances in the feed. As long as applicable EU feed legislation is followed, consuming *A. domesticus* as a novel food does not pose safety concerns (Turck et al., 2022). The epitopes of *A. domesticus* proteins share homology with crustacean and mite allergens, namely tropomyosin and arginine kinase, suggesting that this may lead to cross-reactivity and Immunoglobulin E (IgE)-mediated allergenicity. This homology implies a risk of allergic reactions in exposed individuals, primarily via inhalation, although there is also a risk by ingestion (Pali-Schöll et al., 2019). Thermal processing, such as proteolysis, microwave vacuum drying, or tray drying, can alter protein solubility and cross-allergenicity by degrading or masking IgE-binding epitopes. Consequently, their ability to trigger allergic reactions is reduced (Hall & Liceaga, 2021; Khammeethong et al., 2024). Additionally, high temperatures can initiate Maillard reactions, which modify the structure of proteins and reduce their allergenicity by changing how epitopes are recognized (Pali-Schöll et al., 2019), though they may still retain some immunogenic potential (De Marchi et al., 2021).

Regarding the presence of toxins in insects, they can either

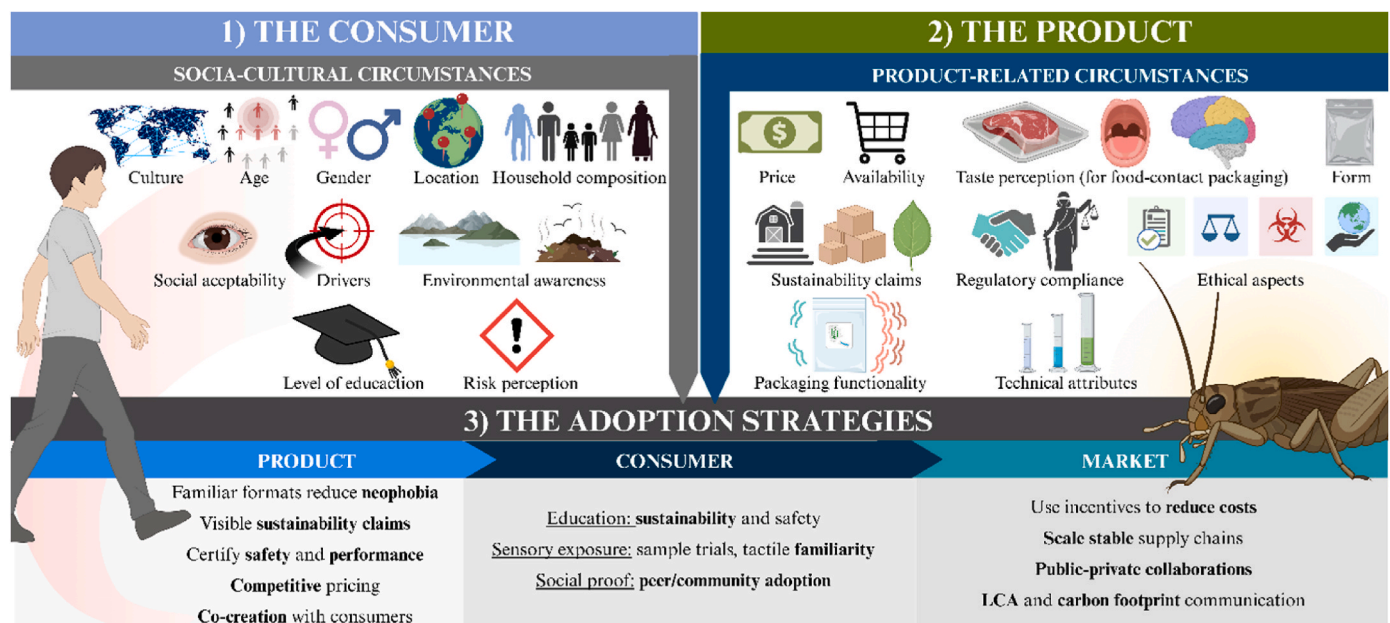


Fig. 4. Factors affecting consumer adoption of insect-derived food packaging.

synthesize them internally or accumulate them from their environment, particularly from the plants they consume or the substrates in which they are bred (Kachel et al., 2018; van der Fels-Klerx et al., 2018). A study of *A. domesticus* found 52 allergy-causing proteins belonging to 15 different allergen families. Among these were AF007: EF-hand family proteins; AF054, tropomyosins; and AF002, heat shock protein Hsp70 (Bose et al., 2021). Currently, there is no evidence suggesting that *A. domesticus* produces reactive, irritating, or endogenous toxins when used for food applications during the studied life stages (van der Fels-Klerx et al., 2018).

Primary pathways of heavy metal accumulation in crickets (Cd, Pb, Hg, and As) stem from bioaccumulation and bioconjugation as they feed on polluted soil, plants, and agricultural waste, predominantly in areas near mineral extraction or large-scale industrial operations (Malematja et al., 2023; Pilco-Romero et al., 2023). While levels of heavy metals in *A. domesticus* have not been reported above the minimum value set by Regulation (EC) No. 1881/2006 (Siddiqui et al., 2024; Regulation, 2006), the European Food Security Authority (EFSA) initially quantified Pb levels of up to 0.27 mg/kg in *A. domesticus*. After the substrate was changed, however, the concentration fell to below 0.096 mg/kg, within the safe threshold. The insect composition remained unchanged despite the change in substrate. Although EU legislation does not establish specific limits for insects, the levels of metals are below the maximum limits (ML) allowed in other foods (Turck et al., 2024). Given this, concerns about the safety of cricket-derived materials emerge, especially if these metals accumulate in the final products.

7.2. Consumer acceptance, legislation, and commercialization

Consumer acceptance is still an impediment to the use of insects or their derivatives as a substitute for petroleum-based packaging materials, even though this biotechnological solution is gaining popularity (Weng et al., 2023). Research indicates that compared to consumers in Western nations, those in Africa, Asia, and Latin America are more accepting of entomophagy. However, in Western nations, psychological barriers such as neophobia, unfamiliarity, disgust, and limited awareness hinder adoption (Abro et al., 2025; Verneau et al., 2021). Psychological barriers may be encountered less often in packaging applications than in food applications. However, insects are still perceived negatively, which could potentially affect their marketability (Alhujaili et al., 2023). When marketing insect-based products, there are two main strategies that should be considered to enhance consumer trust. First, the design of the product should have attributes that will encourage acceptance, such as transparent communication about taste and safety, sample tasting, competitive pricing, sustainability claims, and regulatory compliance. Second, marketing strategies should be developed to attract target consumer segments by highlighting benefits that resonate with each group (Herbert & Beacom, 2021; Puteri et al., 2023). These benefits could encompass health, novelty, or environmental impact. Using familiar product formats will also increase acceptance (Fig. 3) (Alhujaili et al., 2023).

In the EU, regulations on the use of insect-derived polymers, such as chitin and chitosan, in food packaging have progressed more slowly than the consumption of edible insects. Despite the categorization of *A. domesticus* as a novel food under specific EU regulations (EU No. 2015/2283), a harmonized framework addressing the use of these biopolymers in packaging materials remains elusive (Regulation (EU) 2015/2283 of November 25, 2015 on Novel Foods, 2018). The Packaging and Packaging Waste Regulation (PPWR) (EU) No. 2025/40 and the Circular Economy Action Plan (CEAP), in line with the European Green Deal, aim to reduce the disposal of packaging waste, promote the use of biodegradable materials, and facilitate the transition to a circular economy (Regulation 2025/40 of 19 December on, 2024). These initiatives have the potential to facilitate the implementation of cricket-derived biopolymers as active packaging due to their proven ability to meet safety and functionality standards.

The commercialization of chitin and chitosan, along with other cricket-derived biopolymers, is hindered by the difficulty of optimization and scaling up extraction and purification processes (Rehman et al., 2023). The primary causes are inconsistent quality due to unpredictable biological processes, high resource and capital costs, as well as energy-inefficient large-scale equipment and lacking environmental and local impact assessments (Shetranjiwalla & Ononiwu, 2025). Despite the major issues facing the industry, the use of biodegradable polymers is supported by environmental benefits such as the regeneration of raw materials, biodegradation, and the reduction of carbon dioxide emissions that lead to global warming (Samir et al., 2022). Overall, commercializing cricket-derived active packaging, overcoming public scepticism, and ensuring final product designs are consistent with the principles of the circular economy will call for a collaborative effort among policymakers, industry stakeholders, and academia (La Barbera et al., 2020; Moshkbid et al., 2024).

8. Advantages and disadvantages of the use of orthoptera-based biopolymers for food packaging

The use of Orthoptera biopolymers in food packaging materials presents sustainability and environmental benefits as orthopterans can be farmed on a small ecological footprint, requiring less land, water, and feed compared to crustacean or petroleum-based sources (Mermann et al., 2025; Rehman et al., 2023). Furthermore, the Orthoptera-based biopolymers have demonstrated good film-forming ability as the chitosan extracted from Orthoptera can form transparent, flexible, and cohesive films, suitable for coatings or standalone packaging films (Malm et al., 2021; Triunfo et al., 2022; Mei et al., 2024). The packaging materials made from insect-based biopolymers showed adequate barrier properties, exhibiting good oxygen and carbon dioxide barrier capacity, and helping to preserve food freshness and extend shelf life (Mwita et al., 2024). Moreover, the insect-derived biopolymers show natural bioactive properties, making them ideal for active food packaging (Lone, Bhat, et al., 2025; Singh et al., 2023, 2024). Additionally, the Orthoptera-based packaging materials are non-toxic and edible, suitable for direct food contact and even edible coatings, attesting their edibility and safety (Inthorn et al., 2024; Malm et al., 2021).

Although Orthoptera biopolymers in food packaging materials present undeniable advantages, their use at a large level poses some concerns. For instance, the industrial production of Orthoptera biomass is still emerging, so large-scale and cost-effective supply chains are not yet established. Likewise, the Orthoptera species differ significantly in chitin content, degree of acetylation, and molecular weight, which causes inconsistent material properties (mechanical strength, barrier capacity) (Kaya et al., 2015) and therefore can compromise the standardization for packaging applications. To date, psychological barriers are a major blocking stone for the use of insects for the production of food packaging materials in many areas of the world. These barriers have to be alleviated through public and private actions.

9. Conclusions and future prospects

A. domesticus, *G. sigillatus* and *L. migratoria* are the common Orthoptera species used as sources of biopolymers for the formulation of sustainable, edible and bioactive food packaging materials. Alkaline extraction remains the most widely used method for protein recovery from crickets due to its high yield and solubility, while acid-based methods can also be effective under specific conditions. The extraction parameters strongly influence the yield and quality of biopolymers obtained from Orthopterans, and alternative methods can have better results with lower environmental damage. Emerging technologies such as PEF, microwave, ultrasound, and fermentation, along with enzymatic solutions, have shown potential to enhance extraction efficiency while preserving the functionality of the biopolymers. These macropolymers exhibit remarkable potential for the development of food packaging

materials, due to their biodegradability, biocompatibility, and functional properties.

Research and legislation initiatives and awareness should arise to facilitate the implementation of Orthopteran-derived biopolymers as active packaging materials. Increasing research is focused on improving the mechanical strength and water resistance of the packaging materials made from Orthopteran-derived biopolymers. Orthopteran-derived biopolymers should be combined with other biopolymers (e.g., starch, PLA, cellulose) to increase the efficacy of the packaging materials. Furthermore, Orthopteran-derived biopolymers should be used to create nanocomposites with enhanced barrier and thermal properties. Moreover, emerging technologies like electrospinning, nanoencapsulation, and bio-blending should be implemented in order to enhance the potential of Orthopteran-derived biopolymers for high-performance food packaging.

CRedit authorship contribution statement

Oscar Zannou: Conceptualization, Investigation, Visualization, Validation, Data curation, Writing – original draft, Writing – review & editing. Barbara Conti, Linda Abenaim, João Pedro Krauspenhar Lopes, Custodio Lobo Roriz, Sandrina A. Heleno, Marcio Carochi, Paula Barciela and Miguel A Prieto: Investigation, Visualization, Validation, Data curation, Writing – original draft. Gulden Goksen: Conceptualization, Investigation, Data curation, Validation, Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used DeepL and Quillbot in order to improve the readability and language of the manuscript. After using these tools/services, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

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.

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Data availability

Data will be made available on request.

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