detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

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INSECTERA: GREEN TRANSITION TOWARDS ENVIRONMENTAL SUSTAINABILITY BASED ON A CIRCULAR ECONOMY

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Article Info:
Received:
17 May 2025
Revised:
19 September 2025
Accepted:
31 October 2025
Available online:
17 November 2025

Keywords:
Insect waste valorization
Circular economy
Chitin
Chitosan
Sustainable chemistry

ABSTRACT

Extracting valuable platform chemicals from waste biomass is a crucial part of the path to developing a circular, sustainable materials economy. As a particularly significant example, recent developments at the insect biorefinery – utilization of insect biomass – are herein discussed. The focus is placed on the valorisation of *Hermetia illucens* (commonly known as Black Soldier Fly, BSF) waste created during their industrial production process. In particular, pupae exuviae of BSF are used in studies aimed at obtaining useful raw materials, such as chitin and chitosan, for other industry sectors, namely the health industry.

1. INTRODUCTION

The insect industry is gaining global recognition for its role in sustainable waste management and the development of high value bioproducts. Black Soldier Fly (BSF), mealworms, and crickets are among the most widely farmed species due to their rich protein content, rapid growth, and minimal environmental footprint. Of these, the Black Soldier Fly (BSF) stands out for its remarkable ability to convert organic waste into valuable resources: BSF larvae efficiently break down food waste and agricultural byproducts (e.g., fruit and vegetable wastes, kitchen wastes, and brewery's byproducts) (Alciatore et al., 2024), reducing environmental pollution while generating protein, oil, and frass (insect manure) for various applications.

In food and animal feed, insects provide a sustainable alternative to traditional protein sources like soy and fishmeal, while agricultural applications focus on organic fertilizers and pest control. Beyond its well-known use in these sectors, BSF waste is now attracting attention in the cosmetic and pharmaceutical industries. The oils and bioactive compounds derived from BSF biorefinery offer potential as sustainable ingredients for skincare and personal care products (Lai-Foenander et al., 2024). Rich in antimicrobial peptides, fatty acids, and antioxidants, these insect-derived compounds are being explored for their moisturizing, anti-aging, and protective properties.

Portugal has been making significant developments in the insect industry, focusing on sustainable food production and innovative applications. Recently, the Mobilizing Agendas for Business Innovation, framed in the Recovery and Resilience Plan (RRP) (https://recuperarportugal.gov.pt/), emerged with the objective of consolidating and expanding synergies between the Portuguese business fabric and the scientific and technological system, contributing to the increase in the competitiveness and resilience of the Portuguese economy, based on R&D, innovation and the diversification and specialization of the productive structure.

It was in this context that, in 2023, the InsectERA Mobilizing Agenda (https://www.insectera.pt/english/) was created, bringing together stakeholders from across the value chain who want to explore the potential of insects as a bioindustrial tool and bioindustrial solutions. The InsectERA Agenda covers the entire innovation cycle, from Research & Development to the manufacturing and commercialization of products on the market, based on technologically advanced production methods.

Our task within the Agenda is to valorise insect biowaste through its technological conversion into industrial raw materials and high-value-added products. In particular, pupae exuviae of insects such as Hermetia illucens (Black Soldier Fly, BSF) are used in studies aimed at obtaining useful components, such as chitin and chitosan for the health industry. These BSF derivatives are directly applied in the

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production of new high-value-added products, such as cosmetics for dermoatological and haircare applications.

The industrial production of Black Soldier Fly involves several steps, according to its life cycle (Figure 1).

For all stages of the life cycle, except for the pupal stage, the BSF form is utilized and commercialized, generating value. Therefore, throughout the entire BSF cycle, only the pupae are considered waste (Figure 2), as it has no valuable application so far.

Our task is, therefore, to change this paradigm and identify a commercially viable product, thereby completing the BSF-based circular economy. The BSF pupae exuviae are processed to extract their chitin, as explained in the following section.

2. CHITIN EXTRACTION PROCESS

Chitin is one of the most abundant (with annual biological production levels of ca. 10^{11} tonnes – Tharanathan et al., 2003), natural polysaccharides, a linear polymer composed of repeating β-(1,4)-N-acetylglucosamine units (i.e., between 55% and 98% of units by weight, preferably between 75% and 90% of units by weight, Figure 3) that has generated the most interest.

In insects in particular, chitin makes up between 3 and 60 per cent of their exoskeleton.

Extracting chitin from BSF pupae exuviae requires several steps (Figure 4):

- Milling the exuviae;
- Demineralization of exuviae in acid medium;
- Deproteination of exuviae in basic medium;
- Isolation of the chitin;
- Purification of isolated chitin.

FIGURE 2: Life cycle of *Hermetia illucens* (Black Soldier Fly, BSF) illustrating the industrial raw-materials obtainable from each stage. Currently the pupal stage has no applications.

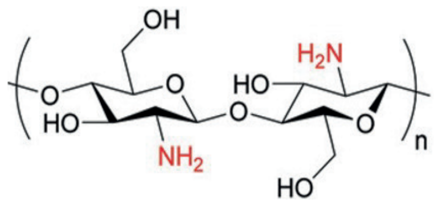

FIGURE 3: Repetitive unit representation of the biopolymer chitin.

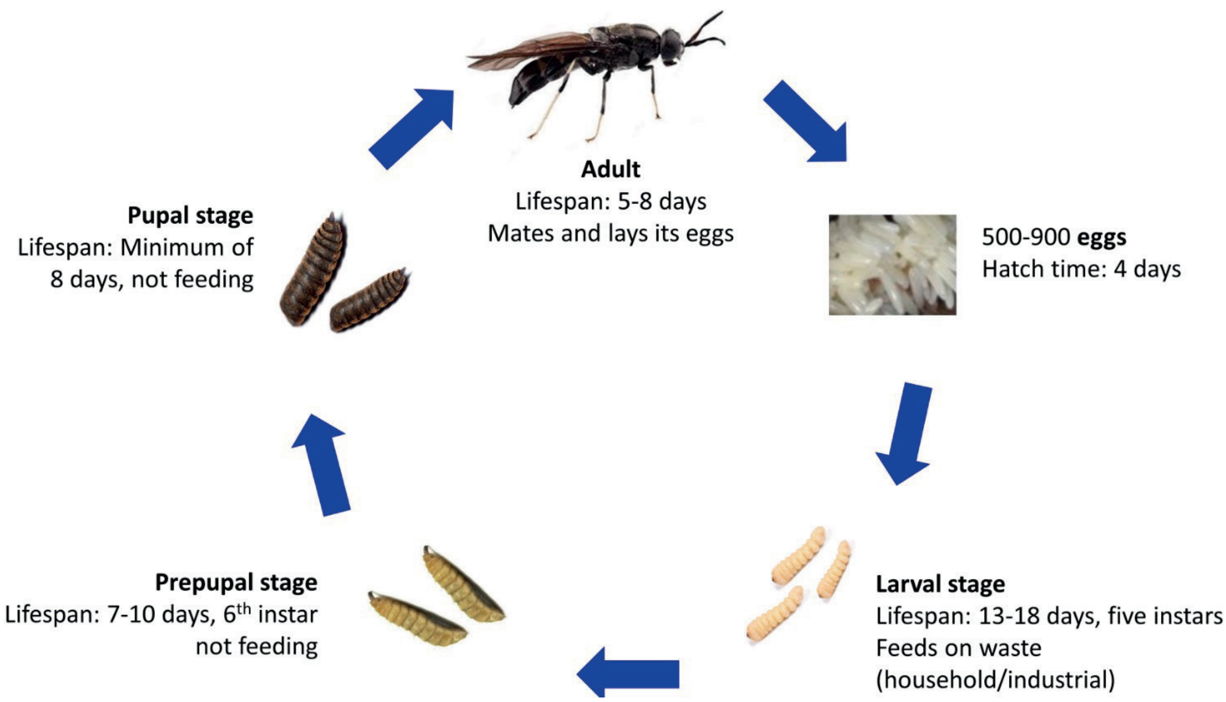

FIGURE 1: Life cycle of *Hermetia illucens* (Black Soldier Fly, BSF).

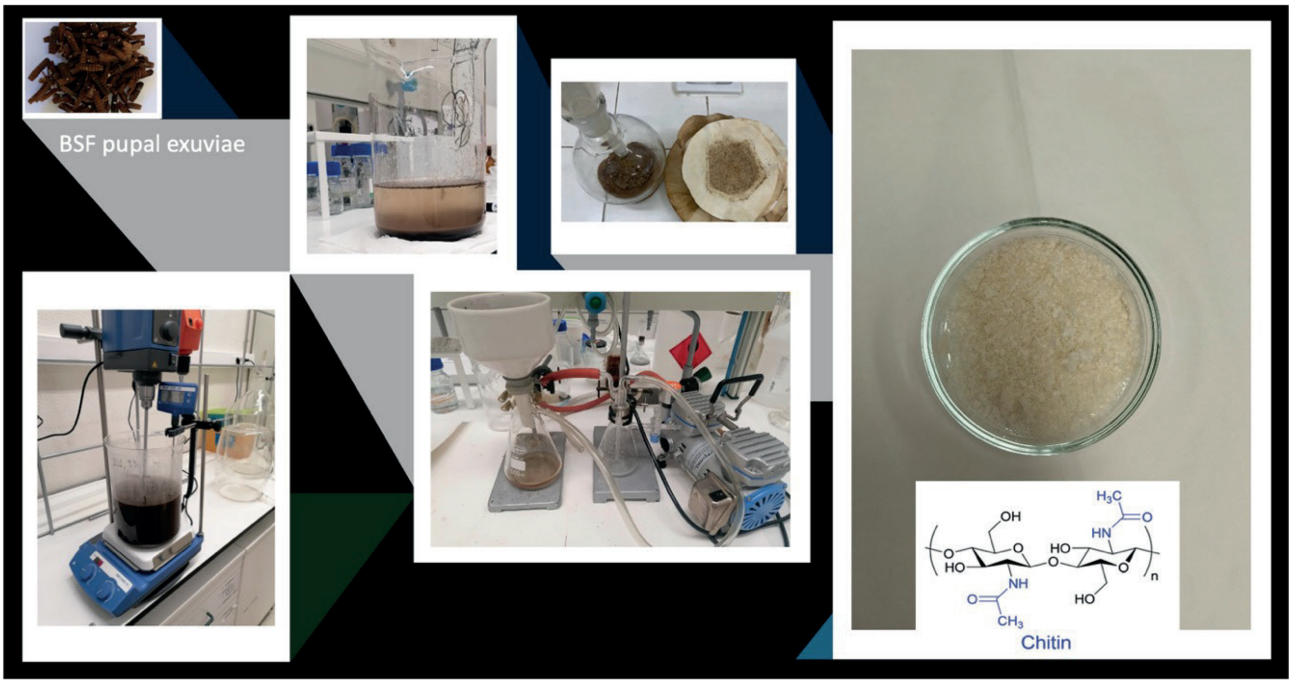

FIGURE 4: Extraction of chitin from BSF pupal exuviae.

The technological and ecological aspects of this lab protocol developed at IST are considered by including dual-purpose reagents that can preserve the characteristics of the purified chitin and can be produced from low-cost biomass.

3. CHITOSAN PRODUCTION PROCESS

Chitin can undergo deacetylation, i.e., the conversion of amide functions into amine functions, giving rise to chitosan (Figure 5), a water-soluble biopolymer that has great chemical versatility as well as antibacterial and antifungal properties.

In fact, chitosan already has a worldwide market that reached a value of USD 2.49 billion in 2020 and a compound annual growth rate (CAGR) of approximately 12% is projected between 2021 and 2026.

It is known that the degree of deacetylation of chitin as well as the average molecular weight and polydispersity of the chitosan obtained play a crucial role in the properties of chitosan-based biopolymers, and consequently in their applications. For example, the use of a chitosan biopolymer with a high average molecular weight maximises its antimicrobial effect (Matica et al., 2019) and limits trans-epidermal water loss or skin irritation (Feng et al., 2021).

Thus, one of the challenges of this work was to provide a process for producing chitosan biopolymers with a high average molecular weight and a high degree of deacetylation and purity that is, at the same time, environmentally favourable both in terms of energy and resource consumption and in terms of reducing waste generation.

4. CONCLUSIONS

With the increasing global demand for sustainable solutions, combined with government support and technological advancements, the insect industry is poised to

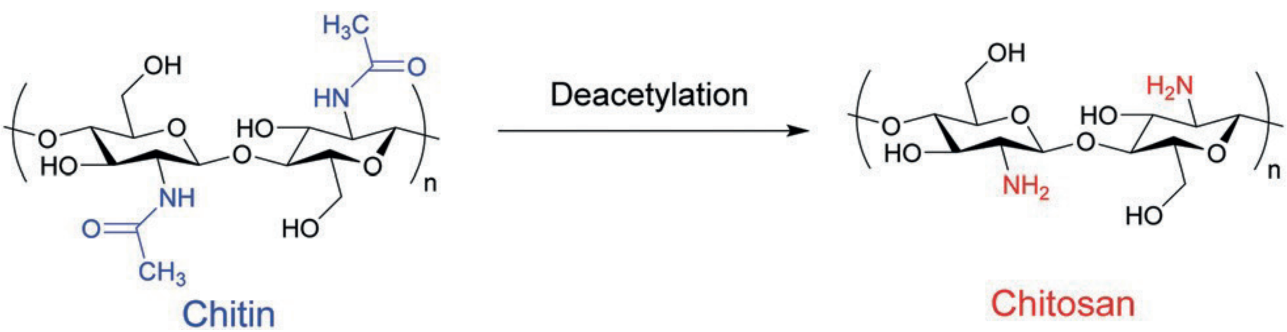

FIGURE 5: Production of chitosan by deacetylation of chitin.

transform multiple sectors, driving circular economy practices and minimizing environmental impact.

The process developed within the InsectERA Mobilizing Agenda effectively utilizes surplus biomass from the agri-food sector - specifically BSF exuviae - allowing it to be reintegrated into the original ecosystem, closing the economic circle. This approach not only prevents waste but also promotes the use of insect-based products.

ACKNOWLEDGEMENTS

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