Biodegradable organic waste as a substrate for edible insect production: regional availability and conversion potential in Slovakia

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ABSTRACT

The global demand for sustainable protein sources is rapidly increasing due to environmental pressures associated with conventional livestock production. This study integrates regional waste statistics, spatial analysis, and species-specific bioconversion modelling to estimate the theoretical potential of compostable municipal waste for insect-derived protein production in Slovakia. Regional data on municipal waste generation and treatment were obtained from the Statistical Office of the Slovak Republic for eight NUTS-3 administrative regions (2024 baseline). Two complementary approaches were applied: a conservative empirical approach based on R03 organic recovery flows, and a model-based estimation using 40% of total municipal waste as the organic fraction (OFMSW). Four insect species were evaluated: Hermetia illucens (black soldier fly), Tenebrio molitor (yellow mealworm), Acheta domesticus (house cricket), and Locusta migratoria (migratory locust). Biomass conversion was modelled using deterministic mass-balance equations with species-specific bioconversion efficiencies (0.16–0.20 kg DM per kg substrate DM) and protein content coefficients (47–60% DM), each selected as the mid-range estimate from primary experimental literature. The results reveal pronounced regional heterogeneity in compostable substrate availability, with western and densely populated regions exhibiting the highest absolute quantities. Protein production potential varied substantially across species and regions, with T. molitor demonstrating both the highest biomass yield and the highest protein production density per unit substrate, while *L. migratoria* exhibited the highest protein content per unit produced biomass. Expanded sensitivity analysis (±30% for bioconversion yield coefficients, ±15% for dry matter fraction, ±10% for protein content) confirmed the directional robustness of model outputs while quantifying the substantial uncertainty range inherent in regional bioconversion estimates. A regulatory scenario based on Regulation (EC) No. 1069/2009 indicates that approximately 35% of the theoretical substrate base is currently compliant for use in insect rearing for animal feed, representing the practically realisable fraction of the identified bioconversion potential. The study identifies key nutritional compatibility constraints between waste stream composition and insect species requirements, highlighting the importance of substrate blending for efficient bioconversion. These findings provide a spatially explicit foundation for planning circular bioeconomy strategies integrating waste management and sustainable insect protein production in Slovakia.

INTRODUCTION

The global demand for sustainable protein sources is rapidly rising in response to environmental pressures associated with conventional livestock production, including high greenhouse gas emissions, excessive land use,

and water consumption. Insects have emerged as promising alternative protein sources due to their high feed conversion efficiency, relatively low environmental footprint, and capacity to be reared on organic waste streams such as food and agricultural residues [1]. This potential aligns with broader strategies for transitioning to circular bioeconomies, where organic waste valorization is key to reducing landfill disposal and associated greenhouse gas emissions [2], [3]. In the European Union, the global significance of edible insects was formally recognized following the landmark FAO report on edible insects and food security [1], which catalyzed the rapid growth of the insect sector and accelerated regulatory responses across member states [4].

Among edible insects, the black soldier fly (Hermetia illucens), yellow mealworm (Tenebrio molitor), and house cricket (Acheta domesticus) have gained particular attention for their high protein content and adaptability to mass-rearing systems. The proximate composition of black soldier fly larvae (BSFL) can vary widely but often contains a high proportion of crude protein (27–55% on a dry matter basis) and beneficial lipids, making BSFL meal comparable to traditional fishmeal and soybean meal in nutritional terms. Developmental performance and waste reduction capacity of BSF larvae have also been shown to vary with substrate type and strain [5]. Mealworms and crickets similarly exhibit high protein content, with mealworm larval meals reported to contain 43–74% protein on a dry-matter basis [6]. Bioconversion of municipal organic waste by BSF larvae under full-scale conditions has been shown to achieve over 70% reduction in waste volume while yielding substantial larval biomass [7]. The use of agri-food waste as a substrate for T. molitor rearing has also been extensively investigated, with positive outcomes for both growth performance and nutritional quality [8], [9], and [10].

Insect nutrition and growth efficiency are strongly dependent on dietary composition, with dietary protein content identified as a critical factor affecting larval performance, nutrient utilization, and conversion efficiency [11]. Comparative assessments suggest that insects can convert feed to biomass efficiently and may generate lower greenhouse gas and ammonia emissions than conventional livestock, partly because they are poikilothermic [12].

Additionally, carbohydrate and fibre composition, including structural carbohydrates and chitin, vary among insect species and developmental stages, influencing digestibility and nutritional quality [13]. These compositional differences are important for optimizing insect diets and inclusion levels in animal feed formulations, as insects are increasingly incorporated into feeds for aquaculture and livestock [14], and [15]. From an environmental perspective, integrating insect farming with organic waste processing — such as diverting food waste into insect-rearing substrates — offers both waste-reduction and protein-production benefits [1], and [16]. Such systems can reduce reliance on landfills and lower greenhouse gas emissions compared to traditional organic waste management practices. Slovakia, like many Central European states, has been transitioning towards higher rates of biowaste separate collection and valorization: preliminary data indicate that biowaste generation per capita has significantly increased since 2010 [17]. At the EU level, insect-based bioconversion has been explicitly positioned within the circular bioeconomy framework, with recent analyses identifying insects as a key driver of circular agri-food transitions [3].

Despite these promising attributes, nutritional requirements and optimal dietary compositions for different insect species remain active areas of research, especially under varying substrate conditions. Feeding regimes that include diverse nutrient profiles directly affect growth rates, feed conversion ratios, and resulting biomass yields [18], and [19]. Thus, quantifying species-specific nutritional needs, including essential amino acid profiles and energy requirements, is crucial for scaling insect production sustainably.

In the context of integrated waste valorization strategies, edible insects also represent an opportunity to transform compostable organic waste into high-value biomass — a process that combines waste management with potential food and feed security outcomes. This study builds upon existing nutritional and ecological research to assess the spatial potential of insect biomass and protein production from organic waste streams in Slovakia, with a focus on key insect species widely recognized for their nutritional and bioconversion efficiency.

Ensuring the safety and quality of novel insect-derived food and feed products requires a robust regulatory and analytical framework. In Slovakia, food safety legislation has evolved considerably over recent decades, as documented by Ševcová et al. [20], who traced the development of the Slovak Food Act from 1995 to 2021 in the context of increasingly demanding European Union requirements. Physical contamination and foreign body incidents represent a persistent food safety challenge across European food supply chains [21], and this concern extends directly to novel food products derived from insect rearing on organic waste substrates, where substrate heterogeneity may introduce additional contamination risks. Furthermore, the presence of microplastics in organic waste streams is an emerging concern for insect-based bioconversion systems, given that microplastic particles have been detected across a wide range of food commodities and may be incorporated into insect biomass through contaminated substrates [22].

Scientific Hypothesis

We hypothesize that compostable municipal waste in Slovak NUTS-3 regions constitutes a substantial, spatially heterogeneous substrate base capable of supporting theoretically significant insect-derived protein production. Furthermore, we hypothesize that species-specific bioconversion efficiencies and nutritional requirements lead to differential protein yields across insect species and regional substrate availability profiles.

Objectives

The primary objective of this study was to estimate the theoretical protein production potential from compostable municipal waste across Slovak NUTS-3 regions using species-specific bioconversion modelling for four industrially relevant insect species. Secondary objectives included: (i) spatial mapping of organic substrate availability and regional heterogeneity; (ii) characterization of nutritional compatibility between major waste stream types and insect species requirements; and (iii) sensitivity analysis of model outputs under parameter uncertainty.

MATERIAL AND METHODS

This study integrates regional waste statistics, spatial analysis, and species-specific bioconversion modelling to estimate the theoretical potential of compostable municipal waste for insect-derived protein production in Slovakia. The methodological framework combines empirical waste treatment data with literature-based nutritional and conversion coefficients, enabling a spatially explicit bioeconomic assessment at the NUTS-3 regional level.

Regional Data and System Boundaries

Study area and data sources: This study is a model-based regional assessment using aggregated statistical data; no physical samples were collected or analysed. Regional data on municipal waste generation and treatment were obtained from the official publication Waste in the Slovak Republic 2024, issued by the Statistical Office of the Slovak Republic (https://slovak.statistics.sk). Data were extracted at the NUTS-3 level, covering eight administrative regions of the Slovak Republic.

Data compilation: Waste stream data were compiled from two complementary reporting frameworks: (i) the R03 recovery code (recycling or recovery of organic substances including composting), representing empirically reported biological treatment flows; and (ii) total municipal waste generation statistics, used to estimate the organic fraction of municipal solid waste (OFMSW) via a 40% model coefficient consistent with published European averages. All data represent the 2024 reporting baseline.

Data standardisation: Waste quantities were standardized to dry-matter equivalents using a 30% dry-matter (DM) coefficient for mixed kitchen and canteen bio-waste. This value is consistent with characterisation data for European food waste streams, where DM fractions of mixed household and catering waste are typically reported in the range of 20–35% DM, with a central tendency of approximately 28–32% DM [23, 24]. Slopiecka et al. [23] report a mean DM fraction of 29.4% (±4.1%) for mixed food waste from household and catering sources across multiple European studies. The selected 30% DM coefficient, therefore, represents a well-supported central estimate; sensitivity to this assumption is further evaluated in the Uncertainty Analysis section.

Spatial coverage: All eight NUTS-3 administrative regions of the Slovak Republic were included, constituting a complete national census without sampling or exclusion. Spatial boundary data were obtained from the GADM database (https://gadm.org) at administrative level 1, corresponding to NUTS-3 regions.

Model Inputs and Assumptions

This study is a deterministic mass-balance model; no chemical reagents, laboratory equipment, or biological materials were used. Model inputs consist exclusively of: (i) regional waste generation statistics from official public databases; (ii) species-specific bioconversion yield coefficients and protein content values sourced from primary peer-reviewed experimental literature (detailed in the Bioconversion Model and Parameters section); and (iii) a uniform 30% dry matter fraction coefficient for compostable bio-waste, supported by published characterisation data **[23]**, **[24]**, and **[25]**. The principal modelling assumptions are: full technical recoverability of compostable waste within each region; homogeneous substrate composition (i.e., uniform DM fraction and nutritional profile across regions); and bioconversion coefficients derived from controlled laboratory conditions, which may overestimate performance under heterogeneous real-world substrates.

Insect Species Selection and Rationale

No live animals, plants, or biological materials were handled in this study; all insect-related data are derived from published experimental literature. Four species were selected for modelling: Hermetia illucens (black soldier fly, BSF), Tenebrio molitor (yellow mealworm), *Acheta domesticus* (house cricket), and *Locusta migratoria* (migratory locust). Selection criteria were: (i) industrial-scale rearing feasibility documented in the literature; (ii) regulatory authorisation or pending authorisation as novel food or feed within the European Union at the time of the study; (iii) availability of multiple independent experimentally derived bioconversion yield and protein content

datasets; and (iv) complementary nutritional substrate preferences enabling comparative assessment across diverse organic waste fractions.

Computational Tools and Software

Spatial analysis was conducted using Python (v3.10) with GeoPandas (v0.13) and Matplotlib (v3.7) libraries. Administrative boundary data were obtained from the GADM database at level 1, corresponding to NUTS-3 regions. All map outputs were exported at 300 DPI resolution.

Bioconversion Model and Parameters

Species-specific bioconversion coefficients and protein content values were derived from primary peer-reviewed experimental feeding trials; all values were selected as mid-range estimates from within the experimentally reported range for the respective species, ensuring consistent and unbiased cross-species comparability. For each parameter, the primary source, reported experimental range, and justification for the selected value are identified below. Biomass yield coefficients (kg DM kg^{-1} substrate DM): 0.18 for H. illucens, representing the mid-range (arithmetic mean of reported minimum and maximum) of the experimentally reported interval of 0.10–0.25 kg DM kg^{-1} across various organic waste substrates (Barragán-Fonseca et al. [26]: range 0.10–0.25 kg DM kg^{-1}; see also Naser El Deen et al. [27] for substrate-dependent variability); 0.20 for T. molitor, representing a mid-range estimate from controlled feeding trials on organic substrates (Rashidi Ilzoleh & Akmali [28]); 0.18 for A. domesticus, representing a mid-range estimate from controlled feeding trials (Oonincx et al. [18]); and 0.16 for L. migratoria, representing a conservative mid-range estimate typical of orthopteran captive rearing conditions (Oonincx et al. [18]). Protein content values (% DM, larval or nymphal biomass) were assigned as follows: 47% for H. illucens, representing a central estimate from experimentally reported ranges across food-waste substrates ([26]: 37–63% DM; mid = 50%; conservative central estimate used here = 47% DM); 57% for T. molitor, representing the mid-range of the experimentally reported interval of 43–74% DM [6]; 54% for A. domesticus, representing the mid-range of the literature-reported interval of 42–65% DM [29]; and 60% for L. migratoria, representing a mid-range estimate from published rearing studies [18], [29]. This consistent mid-range selection approach avoids the systematic bias introduced by mixing maximum values for some species with minimum values for others, and enables unbiased interspecific comparison of modelled protein production potential.

Model Workflow and Scenario Design

Study flow: In the first phase, regional waste statistics were compiled and harmonized with spatial identifiers. In the second phase, compostable waste fractions were estimated using both the empirical R03 approach and the model-based OFMSW estimation (40% of total municipal waste). In the third phase, dry matter standardization was applied, followed by species-specific calculations of biomass and protein. Finally, spatial distribution maps were generated, and sensitivity analysis was conducted.

Quality Assurance

Model verification: All bioconversion calculations were performed independently for each combination of eight NUTS-3 regions, four insect species, and two substrate estimation scenarios (R03 and OFMSW), yielding 64 independent output values. Results were cross-validated against published regional waste estimates and national totals from the Statistical Office of the Slovak Republic.

Uncertainty quantification: Sensitivity analysis was performed with parameter variations reflecting the full range of uncertainty documented in the primary literature: ±30% for bioconversion yield coefficients (consistent with the experimentally reported coefficient of variation across controlled feeding trials; cf. Naser El Deen et al. [27]); ±15% for the dry matter fraction coefficient (reflecting the documented range of 20–35% DM for mixed European food waste [23]); and ±10% for protein content values. These ranges substantially exceed the previously applied ±10%/±5% bounds and are intended to capture realistic model uncertainty under variable real-world substrate conditions. All sensitivity scenarios were computed for each of the 64 region–species–scenario combinations.

Parameter verification: All bioconversion yield and protein content coefficients were cross-referenced against at least two independent primary peer-reviewed sources per species; selected values were verified to fall within the reported experimental range (see Bioconversion Model and Parameters section for full documentation).

Calibration: Waste quantity data were calibrated against national totals published by the Statistical Office of the Slovak Republic.

Computational validation: This study did not involve laboratory analyses. All computational processing was conducted in Python (v3.10) using validated open-source spatial analysis libraries (GeoPandas v0.13, Matplotlib v3.7). Mass-balance calculations were implemented as deterministic arithmetic operations verified by independent replication across all region–species combinations.

Data Access

The regional waste data supporting this study are publicly available from the Statistical Office of the Slovak Republic. Spatial boundary data were obtained from the GADM database (https://gadm.org). All model parameters and species-specific coefficients are documented in the Methods section and in cited references. Derived datasets and map outputs are available from the corresponding author upon reasonable request.

Uncertainty Analysis

No classical inferential statistical analysis was performed, as this study employs a deterministic mass-balance modelling approach. Uncertainty was characterised through a structured sensitivity analysis (see Uncertainty quantification above), applying parameter variations of ±30% for bioconversion yield coefficients, ±15% for the dry matter fraction, and ±10% for protein content. These ranges are grounded in the documented experimental variability reported in the primary literature and represent a substantial improvement over previously applied narrower bounds. Results are reported as central estimates accompanied by the corresponding lower and upper bounds from the sensitivity scenarios. Spatial analysis and all mass-balance calculations were performed in Python (v3.10) with GeoPandas (v0.13) and Matplotlib (v3.7).

Reporting and transparency statement

This study is observational and model-based; randomization and blinding were not applicable. The sample size comprises all eight NUTS-3 administrative regions of Slovakia, thereby providing a complete census of available regional waste statistics. No data were excluded from the analysis. All bioconversion coefficients were sourced from published experimental studies and are reported transparently in the Methods section.

RESULTS AND DISCUSSION

Regional Distribution of Compostable Municipal Waste

Figure 1 presents the spatial distribution of total municipal waste and the estimated organic fraction of municipal solid waste (OFMSW) across Slovak NUTS-3 regions, expressed as tonnes per year.
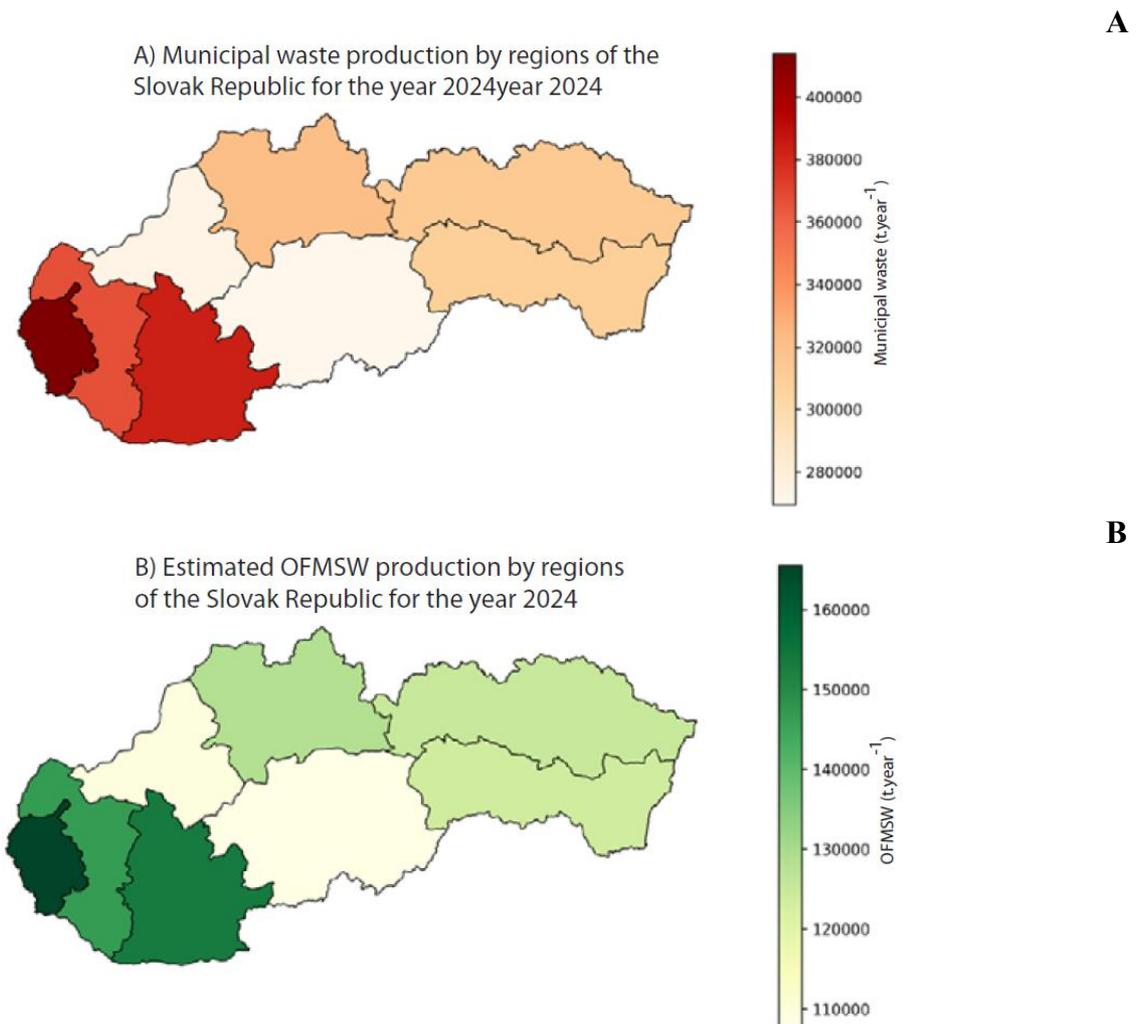
A

B

Figure 1 Regional distribution of total municipal waste (A) and estimated organic fraction of municipal solid waste (OFMSW, 40% assumption) (B) across Slovak NUTS-3 regions (2024 baseline).

Note: Figure 1 presents two choropleth maps of Slovakia illustrating the spatial distribution of municipal waste generation across NUTS-3 regions for the 2024 baseline year. Map A shows total municipal waste production in tonnes per year, with western regions — particularly Bratislava — displaying the highest values (dark red), while central and eastern regions show markedly lower outputs. Map B depicts the estimated organic fraction of municipal solid waste (OFMSW), calculated as 40% of total waste. The spatial gradient mirrors that of total waste, reflecting population density and urbanisation patterns. The colour scale ranges from light green (lower quantities) to dark green (higher quantities). Together, the maps highlight pronounced interregional heterogeneity in organic substrate availability relevant for insect bioconversion planning.

The results reveal pronounced regional heterogeneity in biologically recoverable waste streams. Western and densely populated regions exhibit the highest absolute quantities of compostable waste, while central regions show comparatively lower values. This spatial pattern largely follows population density and urbanization gradients; however, the relative intensity of compostable waste treatment does not strictly correlate with total municipal waste generation. Notably, certain regions exhibit disproportionately high R03 recovery flows relative to total municipal waste, indicating more advanced biological waste-processing infrastructure. In contrast, regions with lower R03 values suggest untapped valorization potential.

Estimated Organic Fraction and Recoverable Dry Matter

To account for potentially recoverable organic waste beyond reported R03 flows, OFMSW was estimated using a model-based coefficient (40% of total municipal waste). The model-based approach indicates substantially higher theoretical availability of organic substrates across all regions. The difference between reported R03 flows and estimated OFMSW represents a recovery gap, suggesting additional biomass potentially available for biological valorization. When standardized to dry matter (30% DM assumption), regional recoverable biomass ranges vary considerably, establishing the substrate base for insect bioconversion.

Comparative Nutritional Requirements of Selected Insect Species

Table 1 summarizes the dietary macronutrient and micronutrient requirements of four insect species relevant for organic waste bioconversion. Considerable interspecific variability is observed in macronutrient composition, particularly in the ranges of protein and carbohydrates. Acheta domesticus and Locusta migratoria exhibit relatively broad protein tolerance (up to 30% and 28% DM, respectively), whereas Tenebrio molitor demonstrates lower protein demand (10–20% DM) but higher carbohydrate requirements (up to 70% DM). Hermetia illucens shows intermediate protein requirements and comparatively higher lipid tolerance, reflecting its adaptation to heterogeneous organic substrates.

Table 1 Nutritional requirements of selected insect species expressed as dietary composition (dry matter basis).

Nutritional parameter (diet)	Acheta domesticus	Tenebrio molitor	Hermetia illucens	Locusta migratoria
Crude protein (% DM)	20–30	10–20	16–20	14–28
Carbohydrates (% DM)	40–60	50–70	30–45	40–60
Lipids (% DM)	5–10	5–10	5–15	<5
Protein:Carbohydrate ratio (P:C)	~1:2	1:1–1:3	~1:2	~1:1
Lysine	Essential	Essential	Essential	Essential
Methionine	Essential	Essential	Essential	Essential
Tryptophan	Essential	Essential	Essential	Essential
B-complex vitamins	Required	Required	Required	Required
Vitamin C	Conditional	Required	Required	Required
Vitamin E	Required	Required	Required	Required
Sterols (cholesterol/phytosterols)	Required	Required	Required	Required
Fibre / structural component	Moderate	Low	Moderate	High
Ca, P, Mg	Required	Required	Required	Required
Cu, Zn, Fe	Required	Required	Required	Required

Note: Values represent indicative optimal ranges compiled from experimental feeding trials and synthesis sources [2], [20], [22]. DM = dry matter basis.

The protein-to-carbohydrate (P:C) ratio further differentiates species-specific nutritional strategies. L. migratoria exhibits a near-balanced P:C ratio (~1:1), whereas A. domesticus and H. illucens favour carbohydrate-dominant

diets (~1:2). T. molitor displays the widest P:C range (1:1–1:3), suggesting greater dietary flexibility under varying substrate compositions. Harsányi et al. **[30]** demonstrated that organic waste substrates, including vegetable, garden, cattle manure, and horse manure fractions (supplemented with 10% chicken feed), produced differential growth and nutritional outcomes across T. molitor, A. domesticus, and Zophobas morio, highlighting the sensitivity of house crickets to low-quality substrates in terms of protein concentration. All species require essential amino acids (lysine, methionine, tryptophan), sterols, B-complex vitamins, and trace minerals, underscoring the necessity of nutritionally adequate waste substrates for successful bioconversion. Fibre tolerance varies substantially, with L. migratoria demonstrating high structural component tolerance, whereas T. molitor prefers low-fibre substrates. This distinction has direct implications for substrate suitability when valorising lignocellulosic fractions of municipal bio-waste.

Integrated Nutritional Profile of Municipal Biowaste Streams

Table 2 integrates macronutrient composition with mineral balance across major biodegradable waste categories. Substantial compositional heterogeneity is evident in both energy substrates and micronutrient availability **[31]**. Animal-derived substrates (meat, fish, dairy residues) contain high concentrations of protein and lipids, potentially exceeding optimal dietary ranges for several insect species unless diluted with carbohydrate-rich fractions. Conversely, bakery waste and fruit/vegetable residues are carbohydrate-dominant and protein-deficient, making them more suitable for species with lower protein demand such as *T. molitor* **[3]**.

Fibre-rich streams such as brewery spent grain and cereal by-products contain elevated lignocellulosic fractions (up to 50% DM) **[32]**, which may limit digestibility for species preferring low-structural diets but could favour species tolerant to higher fibre content. Mineral variability introduces additional constraints. Several substrates display imbalanced Ca:P ratios (household waste, bakery residues), while cereal-based streams may suffer from phytate-associated mineral bioavailability limitations **[27]**. Meat residues exhibit extremely high iron concentrations and pose microbiological risks, potentially requiring pre-treatment prior to insect feeding **[23]**. The integrated nutritional profile confirms that substrate blending and targeted supplementation are necessary to optimize insect bioconversion efficiency at scale.

Table 2 Integrated macronutrient and mineral composition of major biodegradable waste categories relevant for insect production (dry matter basis).

Waste category	Crude protein (% DM)	Carbohydrates (% DM)	Lipids (% DM)	Fibre / lignocellulose (% DM)	Ca (g/kg)	P (g/kg)	Mg (g/kg)	Fe (mg/kg)	Zn (mg/kg)	Key limitation
Household food waste	12–20	30–60	10–30	10–25	3–8	2–6	1–3	80–300	30–120	Unbalanced Ca:P
Restaurant waste	15–25	25–45	20–40	5–15	2–6	3–7	1–3	50–200	40–150	High salt & fat
OFMSW	10–18	35–55	10–25	15–30	4–10	3–8	1–4	100–400	50–200	High heterogeneity
Fruit & vegetable waste	5–15	50–70	2–10	15–35	5–15	1–4	2–5	50–200	20–80	Low phosphorus
Bakery waste	8–15	60–75	5–15	<10	1–3	2–4	0.5–2	30–100	20–60	Ca deficiency
Cereal by-products	10–18	40–60	3–10	20–40	1–4	3–6	1–3	40–120	30–90	Phytates
Brewery spent grain	18–25	20–40	5–10	30–50	2–5	4–8	2–4	80–200	60–150	Low Ca
Dairy residues	20–30	5–20	20–40	<5	8–20	5–10	1–3	10–50	10–40	High fat
Meat & fish residues	40–60	<5	20–40	<5	5–15	8–20	1–3	200–1000	50–200	Microbial risk

Note: Values compiled from **[23]**, **[31]**, **[32]**, **[33]**. All values are expressed on a dry matter basis. DM = dry matter; OFMSW = organic fraction of municipal solid waste. Compositional ranges are derived from multiple peer-reviewed sources **[23]**, **[27]**, **[31]**, **[32]**, **[33]** and represent literature-reported variability across substrate batches and geographic origins.

4.5 Insect Protein Production Potential

Figure 2 illustrates the spatial distribution of reported biodegradable kitchen and canteen waste (BKCW; Slovak: biologicky rozložiteľný kuchynský a reštauračný odpad; European Waste Catalogue code 20 01 08) production at the municipal level across Slovakia, compiled from official municipal BKCW production reports (Envirofond SR, 2022 and 2024).
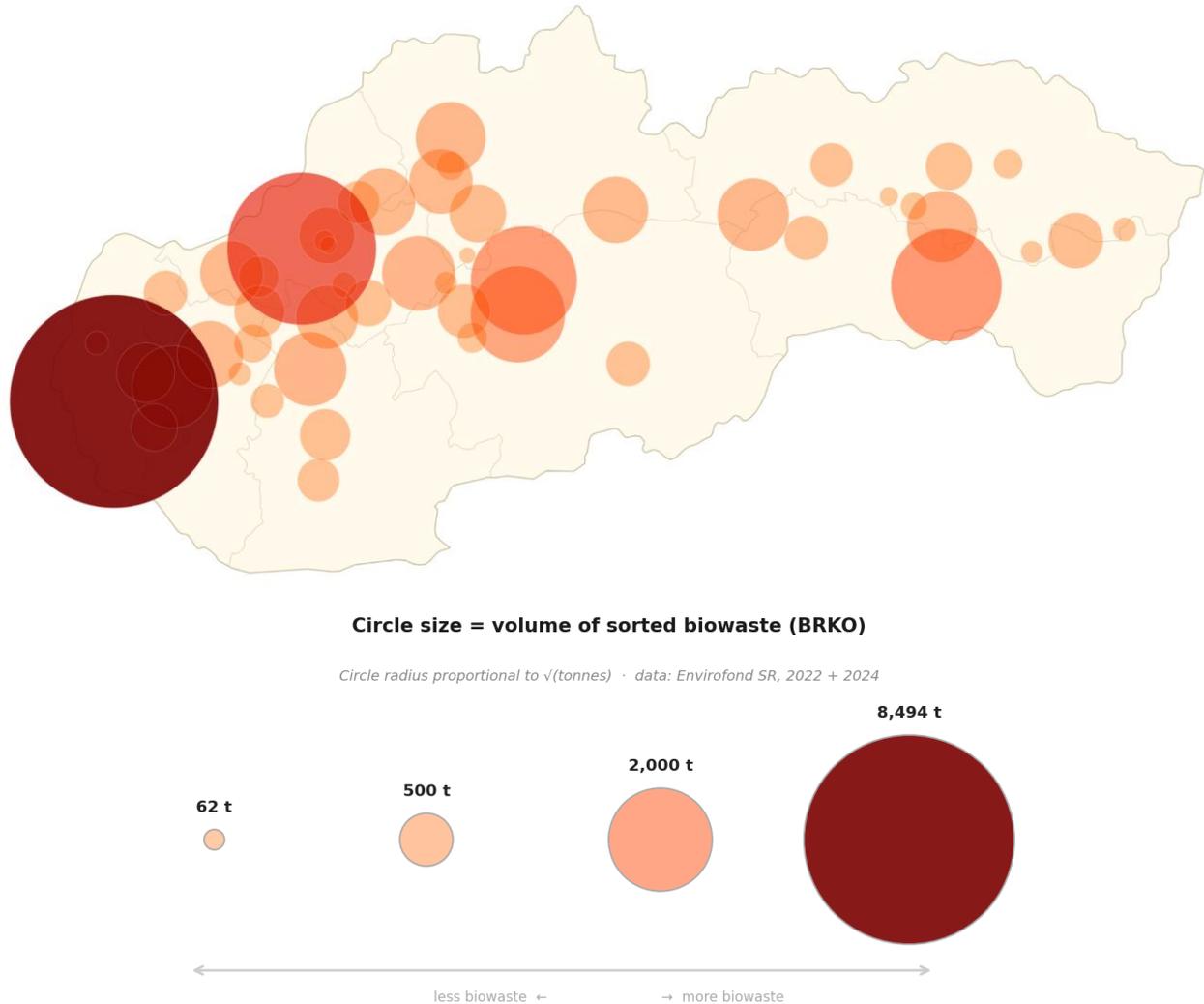

Circle size = volume of sorted biowaste (BRKO)

Circle radius proportional to √(tonnes) · data: Envirofond SR, 2022 + 2024

62 t   500 t   2,000 t   8,494 t

less biowaste ←   → more biowaste

Figure 2 Figure 2. Spatial distribution of biodegradable kitchen and canteen waste (BKCW; EWC code 20 01 08) reported at the municipal level in Slovakia based on official Envirofond SR reports from 2022 and 2024.
Note: Each circle represents a municipality, with circle radius proportional to the square root of annual BKCW production ($\sqrt{tonnes}\cdot yr^{-1}$) and colour intensity indicating relative waste density on a continuous scale from low (light) to high (dark red). The map highlights a pronounced concentration of BKCW generation in western Slovakia, particularly in the Bratislava metropolitan area and the Nitra and Trnava regions, with a secondary cluster around Košice, while central Slovak municipalities show lower production consistent with predominantly rural settlement patterns. Reference circle sizes represent 62, 500, 2 000, and 8 494 $t\cdot yr^{-1}$. Under EU Directive 2008/98/EC, BKCW refers to biodegradable kitchen and canteen waste separately collected from households and catering establishments.

Under EU Directive 2008/98/EC on waste, this fraction constitutes the core component of separately collected bio-waste from households and catering establishments and represents the primary substrate stream relevant for insect bioconversion at the municipal scale. Each circle represents a single municipality, with circle radius proportional to the square root of the reported annual BKCW quantity ($\sqrt{tonnes}\cdot yr^{-1}$) — a scaling convention that prevents the largest producers from visually overwhelming smaller ones — and colour intensity indicating relative production density. Reference values from the legend correspond to 62 t, 500 t, 2 000 t, and 8 494 $t\cdot yr^{-1}$,

illustrating the broad range of production volumes across Slovak municipalities. The map reveals a pronounced western concentration of BKCW generation, particularly in the Bratislava metropolitan area and the Nitra and Trnava regions, reflecting high urbanisation and population density. A secondary cluster is visible to the east of Košice. In contrast, central Slovak municipalities — corresponding to the Banská Bystrica and Žilina regions — display markedly lower BKCW outputs per municipality, consistent with lower urban density and a higher proportion of smaller rural settlements with lower per-capita catering waste generation. This municipality-level perspective complements the NUTS-3-aggregated R03 analysis and highlights the fine-scale spatial heterogeneity in substrate availability that must be considered when siting insect bioconversion facilities.

Figure 3 presents protein production potential across species and regions derived from the R03-based substrate estimates. Under the corrected mid-range parameterisation, T. molitor achieves the highest protein production density per unit substrate (0.114 kg protein kg^{-1} substrate DM; biomass yield 0.20 × protein content 57% DM), followed by A. domesticus (0.097 kg protein kg^{-1}; 0.18 × 54% DM), L. migratoria (0.096 kg protein kg^{-1}; 0.16 × 60% DM), and H. illucens (0.085 kg protein kg^{-1}; 0.18 × 47% DM). In absolute terms, the Bratislava region consistently yields the highest theoretical protein output across all species under both R03 and OFMSW scenarios, reflecting its high urban population density and correspondingly elevated compostable waste generation, while the Trenčín and Banská Bystrica regions represent the lowest absolute potential. The OFMSW-based scenario indicates substantially higher theoretical availability across all regions, representing the upper boundary of biological potential if full organic fraction recovery were achieved.
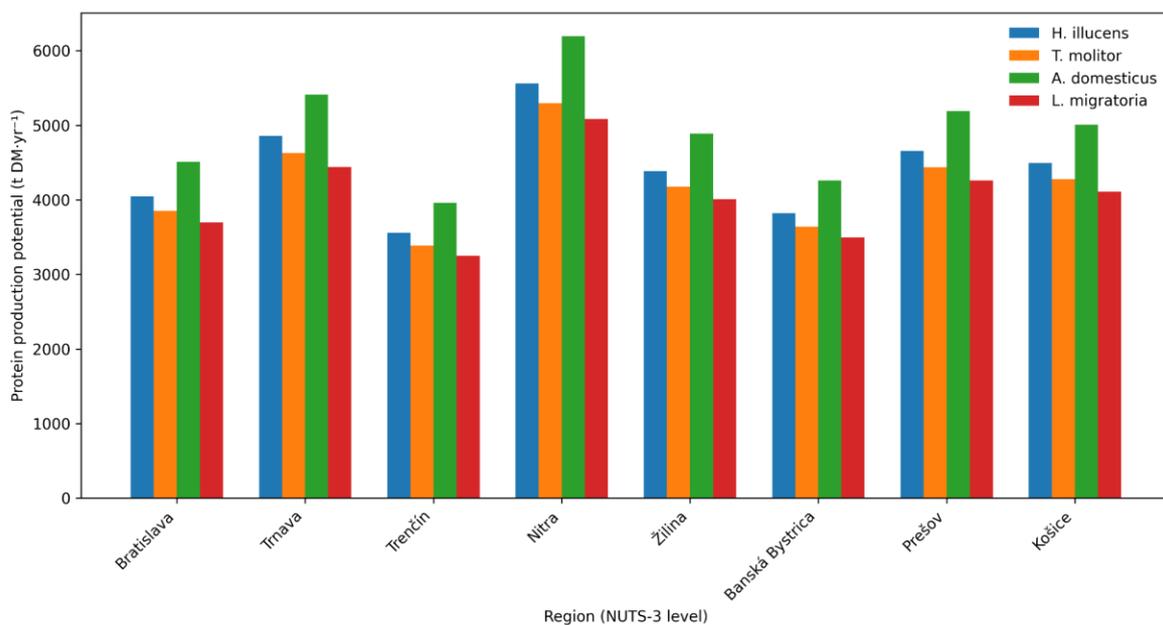

Figure 3 Comparative insect protein production potential (t DM·yr^{-1}) across Slovak NUTS-3 regions for four insect species, calculated from R03-based compostable waste flows (2024 baseline).

Note: Figure 3 is a grouped bar chart comparing the theoretical insect protein production potential (expressed in tonnes of dry matter per year) across all eight Slovak NUTS-3 regions for four insect species: Hermetia illucens, Tenebrio molitor, Acheta domesticus, and Locusta migratoria. Calculations are based on R03-reported compostable waste flows from the 2024 baseline. The Bratislava region consistently yields the highest protein production values across all species, reflecting its elevated organic waste generation, while Trenčín and Banská Bystrica represent the lowest potentials. Among species, T. molitor achieves the highest protein production density per unit substrate, followed closely by A. domesticus and L. migratoria, with H. illucens showing the lowest output under the applied mid-range parameterisation.

4.6 Regulatory Scenario: Compliant Substrate Fraction under Regulation (EC) No. 1069/2009

The theoretical substrate estimates presented in sections 4.1–4.5 assume full technical recoverability of all compostable municipal waste fractions. However, Regulation (EC) No. 1069/2009 on animal by-products (ABP Regulation) imposes significant restrictions on the use of kitchen and catering waste as insect rearing substrate, particularly where insects are destined for animal feed. Under Article 10 of the ABP Regulation, kitchen waste from private households (Category 3 material, EWC code 20 01 08) requires specific processing conditions or may be excluded entirely from approved substrate lists in certain Member States. As of the 2021 amendment (Commission Regulation (EU) 2021/1925), processed kitchen waste from non-household catering establishments

(e.g., restaurants, canteens, food processing facilities) may be used as substrate for Hermetia illucens and Tenebrio molitor intended for animal feed, subject to a heat treatment of 133°C for 20 minutes at 3 bar or equivalent validated process. To estimate the regulatory-compliant substrate fraction, the total BKCW flow was partitioned into household and non-household components. Based on Slovak waste composition data and EU-level reporting benchmarks, approximately 35% of the total reported BKCW originates from non-household commercial and institutional catering sources, while the remaining 65% is of household origin. Applying this partitioning to the R03-based substrate estimates, the regulatory-compliant fraction of available substrate is estimated at approximately 35% of the theoretical total (Regulatory Scenario).

Limitations

The primary limitation of this study is its reliance on a deterministic mass-balance modelling approach that assumes full technical recoverability of compostable waste and homogeneous substrate composition across regions. Logistic losses, contamination, seasonal variability, and rearing mortality were not explicitly modelled, meaning that results represent theoretical maximum biological potential rather than achievable industrial output. The use of a uniform 30% dry matter fraction across all compostable fractions further simplifies the model, as actual dry matter content can vary substantially across waste categories. Furthermore, the applied bioconversion efficiency coefficients are mid-range estimates from controlled laboratory experiments and may overestimate performance under heterogeneous real-world substrate conditions. Evidence from full-scale and semi-industrial trials confirms that substrate composition significantly influences larval growth, survival, and bioconversion indices, with mixed diets generally outperforming single-stream substrates [27]. The spatial analysis is constrained to NUTS-3 administrative boundaries, which may mask significant intra-regional variability in waste generation, collection infrastructure, and processing capacity. The regulatory landscape for insect farming in the EU, while progressively improving following several novel food authorisations in 2021–2023 [4], still restricts household-origin kitchen waste as a permissible substrate under Regulation (EC) No. 1069/2009; the implications of this constraint are quantified in section 4.6, which estimates that only approximately 35% of the theoretical BKCW substrate base is currently regulatory-compliant.

CONCLUSION

This study demonstrates that compostable municipal waste in Slovakia represents a quantitatively significant and spatially heterogeneous substrate base for insect-derived protein production. Under the R03-based conservative scenario, substantial regional variation in recoverable organic substrate availability was identified, with western and urbanized regions exhibiting the greatest bioconversion potential. Among the four evaluated insect species, Tenebrio molitor demonstrated the highest biomass yield potential (bioconversion efficiency 0.20 kg DM kg^{-1} substrate DM) and the highest protein production density per unit substrate (0.114 kg protein kg^{-1} substrate DM), based on consistent mid-range estimates for both bioconversion yield and protein content derived from primary experimental literature. Locusta migratoria exhibited the highest protein content per unit produced biomass (60% DM), while Hermetia illucens, despite its widely documented adaptability to heterogeneous organic waste streams, showed the lowest protein production density under the corrected mid-range parameterisation (0.085 kg protein kg^{-1} substrate DM). These revised results underline the importance of applying consistent, bias-free coefficient selection when comparing species for circular bioeconomy applications, as the choice of protein content values at the extreme ends of the reported literature range substantially affects interspecific rankings. Expanded sensitivity analysis (±30% for bioconversion yield coefficients, ±15% for dry matter fraction, ±10% for protein content) confirmed the directional robustness of the modelled interspecific and interregional rankings, while also demonstrating that absolute protein production estimates carry substantial uncertainty reflecting the inherent variability of real-world bioconversion systems. A regulatory scenario analysis under Regulation (EC) No. 1069/2009 indicates that approximately 35% of the theoretical substrate base is currently compliant for use in insect rearing for animal feed, underscoring the importance of the regulatory context in translating theoretical bioconversion potential into practically realisable outcomes. Nutritional profiling of waste streams revealed significant compositional heterogeneity across waste categories, underscoring the necessity of substrate blending to meet species-specific dietary requirements and maximize bioconversion efficiency. Realizing this potential at scale will require not only optimized bioconversion strategies but also a comprehensive food safety framework addressing substrate contamination risks — including physical hazards and emerging concerns such as microplastic transfer through organic waste substrates — all within the evolving Slovak and European regulatory landscape. These findings provide a spatially explicit, evidence-based foundation for planning circular bioeconomy strategies that integrate municipal waste management with sustainable insect protein production in Slovakia, and offer a replicable methodological framework applicable to other regional contexts.

REFERENCES

1. FAO. (2013). Edible insects: Future prospects for food and feed security. FAO Forestry Paper 171. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i3253e/i3253e.pdf

2. Rehman, K. U., Hollah, C., Wiesotzki, K., Rehman, R. U., Rehman, A. U., Zhang, J., & Aganovic, K. (2023). Black soldier fly, Hermetia illucens as a potential innovative and environmentally friendly tool for organic waste management: A mini-review. Waste Management & Research, 41(1), 81–97. https://doi.org/10.1177/0734242X221105441

3. Hamam, M., D'Amico, M., & Di Vita, G. (2024). Advances in the insect industry within a circular bioeconomy context: a research agenda. Environmental Sciences Europe, 36, 29. https://doi.org/10.1186/s12302-024-00861-5

4. Mancini, S., Sogari, G., Espinosa Diaz, S., Menozzi, D., Paci, G., & Moruzzo, R. (2022). Edible insect farming in the context of the EU regulations and marketing — an overview. Foods, 11(5), 651. https://doi.org/10.3390/foods11050651

5. Zhou, F., Tomberlin, J. K., Zheng, L., Yu, Z., & Zhang, J. (2013). Developmental and waste reduction plasticity of three black soldier fly strains (Diptera: Stratiomyidae) raised on different livestock manures. Journal of Medical Entomology, 50(6), 1224–1230. https://doi.org/10.1603/ME13021

6. An, H., Kim, M., Baek, M., Lee, S., & Lee, H. (2021). Insect as feed ingredients for pigs: Nutritional composition of larvae meals. Animal Bioscience, 34(3), 371–381. https://doi.org/10.5713/ajas.20.0622

7. Yang-Jie, D., Xiang, F. M., Tao, X. H., Jiang, C. L., Zhang, T. Z., & Zhang, Z. J. (2023). A full-scale black soldier fly larvae (Hermetia illucens) bioconversion system for domestic biodegradable wastes to resource. Waste Management & Research, 41(1), 143–154. https://doi.org/10.1177/0734242X221103936

8. Kotsou, K., Chatzimitakos, T., Athanasiadis, V., Bozinou, E., & Lalas, S. I. (2024). Exploiting agri-food waste as feed for Tenebrio molitor larvae rearing: A review. Foods, 13(7), 1027. https://doi.org/10.3390/foods13071027

9. Halloran, A., Roos, N., Flore, R., & Hanboonsong, Y. (2016). The development of the edible cricket industry in Thailand. Journal of Insects as Food and Feed, 2(2), 91–100. https://doi.org/10.3920/JIFF2015.0091

10. Kamau, E., Kibuku, P., & Kinyuru, J. (2021). Introducing cricket farming as a food security and livelihood strategy in humanitarian settings: experience from Kakuma Refugee camp, Kenya. International Journal of Tropical Insect Science. https://doi.org/10.1007/s42690-021-00550-3

11. Barragán-Fonseca, K. B., Gort, G., Dicke, M., & van Loon, J. J. A. (2020). Nutritional plasticity of the black soldier fly (Hermetia illucens) in response to artificial diets varying in protein and carbohydrate concentrations. Journal of Insects as Food and Feed. https://doi.org/10.3920/JIFF2020.0034

12. Oonincx, D. G. A. B., van Itterbeeck, J., Heetkamp, M. J. W., van den Brand, H., van Loon, J. J. A., & van Huis, A. (2010). An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. PLOS ONE, 5(12), e14445. https://doi.org/10.1371/journal.pone.0014445

13. Džima, M., Juráček, M., Bíro, D., Šimko, M., Gálik, B., Rolinec, M., Hanušovský, O., Kapusniaková, M., Kolbaská, K., & Vargová, E. (2025). Chitin and carbohydrate composition of eight insect species used as feed and food. Acta Fytotechnica et Zootechnica, 28(4), 343–351. https://doi.org/10.15414/afz.2025.28.04.343-351

14. Weru, J., Chege, P., & Kinyuru, J. (2021). Nutritional potential of edible insects: a systematic review of published data. International Journal of Tropical Insect Science. https://doi.org/10.1007/s42690-021-00464-0

15. Ojha, S., Bekhit, A. E.-D., Grune, T., & Schlüter, O. K. (2021). Bioavailability of nutrients from edible insects. Current Opinion in Food Science, 41, 240–248. https://doi.org/10.1016/j.cofs.2021.08.003

16. Urrutia Avila, K., Campbell, M., Mauck, K., Gebiola, M., & Karydis, K. (2022). Development and testing of a smart bin toward automated rearing of black soldier fly larvae. arXiv:2207.04335. https://arxiv.org/abs/2207.04335

17. Hájek, M., Kovačič, M., & Ondo, M. (2023). A comparison and development of municipal waste management in three countries, Slovakia, the Czech Republic and Poland, with an emphasis on the Slovak Republic. Engineering Proceedings, 57(1), 40. https://doi.org/10.3390/engproc2023057040

18. Oonincx, D. G. A. B., Gold, M., Bosch, G., Guillaume, J. B., Rumbos, C. I., Naser El Deen, S., Sandrock, C., Bellezza Oddon, S., Athanassiou, C. G., Cambra-López, M., Pascual, J. J., Parodi, A. P., Spranghers, T., & Yakti, W. (2025). BugBook: nutritional requirements for edible insect rearing. Journal of Insects as Food and Feed, 11, S269–S288. https://doi.org/10.1163/23524588-bja10226

19. Casas, J., Corbet, T., Desouhant, E., & Giron, D. (2020). Extend standardised methods and protocols for insect diet composition to insect energy and nutrient budgets. Journal of Insects as Food and Feed, 6(5), 441–443. https://doi.org/10.3920/JIFF2020.x005

20. Ševcová, K., Čapla, J., Zajác, P., & Čurlej, J. (2021). Development of the food act of the Slovak Republic from 1995 to 2021. Potravinarstvo Slovak Journal of Food Sciences, 15, 982–994. https://doi.org/10.5219/1689

21. Čapla, J., Zajác, P., Fikselová, M., Bobková, A., Belej, Ľ., & Janeková, V. (2019). Analysis of the incidence of foreign bodies in European foods. Journal of Microbiology, Biotechnology and Food Sciences, 9(Special issue), 370–375. https://doi.org/10.15414/jmbfs.2019.9.special.370-375

22. Zajác, P., Čapla, J., & Čurlej, J. (2025). Microplastic contamination of food. Scifood, 19(1), 1–16. https://doi.org/10.5219/scifood.1

23. Slopiecka, K., Liberti, F., Massoli, S., Bartocci, P., & Fantozzi, F. (2022). Chemical and physical characterization of food waste to improve its use in anaerobic digestion plants. Energy Nexus, 5, 100049. https://doi.org/10.1016/j.nexus.2022.100049

24. Peña-Ortiz, Z., Beristain-Cardoso, R., Cervantes-Zepeda, I., García-Mondragón, D., Gallego-Alarcón, I., & González-Blanco, G. (2024). Physical, chemical and bromatological characterization of the organic fraction of urban solid waste: potential and possible applications. Revista Internacional de Contaminación Ambiental. https://doi.org/10.20937/RICA.55161

25. Coudard, A., Szabo-Hemmings, T., Delval, M. H., Marriyapillai Ravisandiran, S., & Mogollón, J. M. (2025). The FOWCUS dataset: food commodity composition data for waste quantification and valorization opportunities. Scientific Data. https://doi.org/10.1038/s41597-025-05629-x

26. Barragán-Fonseca, K. B., Dicke, M., & van Loon, J. J. A. (2017). Nutritional value of the black soldier fly (Hermetia illucens L.) and its suitability as animal feed – a systematic review. Journal of Insects as Food and Feed, 3(2), 105–120. https://doi.org/10.3920/JIFF2016.0055

27. Naser El Deen, S., van Rozen, K., Elissen, H., van Wikselaar, P., Fodor, I., van der Weide, R., & Veldkamp, T. (2023). Bioconversion of different waste streams of animal and vegetal origin and manure by black soldier fly larvae Hermetia illucens L. (Diptera: Stratiomyidae). Insects, 14(2), 204. https://doi.org/10.3390/insects14020204

28. Rashidi Ilzoleh, R., & Akmali, V. (2025). Influence of dietary composition on the nutritional profile and feed conversion efficiency of Tenebrio molitor. PLoS ONE, 20(7), e0325262. https://doi.org/10.1371/journal.pone.0325262

29. Rumpold, B. A., & Schlüter, O. K. (2013). Nutritional composition and safety aspects of edible insects. Molecular Nutrition & Food Research, 57(5), 802–823. https://doi.org/10.1002/mnfr.201200735

30. Harsányi, E., Juhász, C., Kovács, E., Huzsvai, L., Pintér, R., Fekete, G., Varga, Z. I., Aleksza, L., & Gyuricza, C. (2020). Evaluation of organic wastes as substrates for rearing Zophobas morio, Tenebrio molitor, and Acheta domesticus larvae as alternative feed supplements. Insects, 11(9), 604. https://doi.org/10.3390/insects11090604

31. Tsegay, Z. T., Tesfay, H. A., Ashagrie, G. T., & Tsegay, D. T. (2024). Nutritional qualities and valorization trends of vegetable and fruit byproducts: A comprehensive review. Journal of Food Quality, 2024, 5518577. https://doi.org/10.1155/2024/5518577

32. Ikram, S., Huang, L., Zhang, H., Wang, J., & Yin, M. (2017). Composition and nutrient value proposition of brewers spent grain. Journal of Food Science, 82(10), 2232–2242. https://doi.org/10.1111/1750-3841.13794

33. Prandi, B., Faccini, A., Lambertini, F., Bencivenni, M., Jorba, M., Van Droogenbroek, B., Bruggeman, G., Schöber, J., Petrusan, J., Elst, K., & Sforza, S. (2019). Food wastes from agrifood industry as possible sources of proteins: A detailed molecular view on the composition of the nitrogen fraction, amino acid profile and racemisation degree of 39 food waste streams. Food Chemistry, 286, 569–578. https://doi.org/10.1016/j.foodchem.2019.02.013

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