The Seybold REPORT

ISSN 1533-9211

DOI: 10.5281/zenodo.23135554

FROM LOCAL PROTEIN TO NUTRITIOUS FOODS: PROCESSING EFFECTS ON THE NUTRITIONAL AND PHYSICOCHEMICAL CHARACTERISTICS OF SAGO GRUBS

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Abstract

Sago worms represent an underutilized local protein resource with considerable potential for the development of nutrient-rich and sustainable food products to support Indonesia's Free Nutritious Meal Program. This study evaluated the influence of different thermal processing methods on the nutritional composition, physicochemical characteristics, fatty acid and amino acid profiles, functional groups, and microstructural properties of sago worms. Samples were prepared as fresh sago worms (SG), air-fried samples (AF; 100 °C for 15 min), and oven-dried samples (OV; 60 °C for 6 h), followed by characterization using proximate analysis, GC–MS, HPLC, FTIR, and SEM. Both thermal treatments substantially decreased moisture content from 67.23% in SG to 13.51% in AF and 12.57% in OV, thereby concentrating protein, fat, and energy. The AF treatment yielded the highest protein content (21.85%), while OV exhibited the greatest fat content (57.60%) and energy value (629.82 kcal/100 g). Oleic acid (omega-9) emerged as a major fatty acid following processing, accounting for approximately 23% in AF and 26% in OV. Glutamic acid was the predominant amino acid across the samples, although thermal treatment modified the relative abundance of several other amino acids. FTIR analysis confirmed that the principal functional groups were largely retained after processing, despite variations in spectral intensity associated with thermal exposure. SEM observations further demonstrated distinct structural modifications, with the porous matrix of fresh samples becoming more compact after air frying, whereas oven drying produced an intermediate microstructure. Overall, these results indicate that controlled thermal processing can enhance the nutrient density and modify the structural characteristics of sago worms, supporting their potential use as a locally sourced protein ingredient for sustainable and nutritious food development.

Keywords: Amino Acids, Essential Fatty Acids, FTIR Signatures, Sago Worms, SEM Morphology.

INTRODUCTION

Sago worms, the larvae of the palm weevil (*Rhynchophorus bilineatus* and related species), are recognized as a traditional food source with high nutritional value and considerable economic potential in eastern Indonesian regions such as Papua, Maluku, Sulawesi and neighboring areas. They develop naturally within the trunks of the sago palm (*Metroxylon sagu*), which is prevalent across these regions. Recent nutrient analyses revealed that these larvae contain notable amounts of protein, lipids, and essential amino acids, making them a valuable dietary component and a local delicacy of indigenous food systems (Trees, 2022). For generations, local communities have valued sago worms as an accessible and culturally significant food, frequently consumed as an alternative nutrient-dense source rich in protein and fats (Kavle et al, 2023). Beyond their nutritional importance, sago worms also contribute to household

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ISSN 1533-9211
DOI: 10.5281/zenodo.23135554

income and local trade, positioning them as a promising resource for both food security and sustainable rural economies (Fasoranti & Ajiboye, 2021).

Sago worms (*Rhynchophorus ferrugineus* and *R. bilineatus*) are recognized for their rich composition of essential nutrients that contribute significantly to human health. They contain 20–30% high-quality protein (dry weight) with a complete profile of essential amino acids, including lysine, leucine, isoleucine, and valine, which support muscle development, immune function, and metabolic processes (Kavle et al., 2023). Their lipid fraction, often exceeding 40%, is dominated by essential fatty acids such as linoleic acid (omega-6) and α-linolenic acid (omega-3), both of which are required for cardiovascular health, inflammation regulation, and neural development (Chinarak et al., 2022). Additionally, sago worms provide key micronutrients including iron, zinc, magnesium, and phosphorus in concentrations comparable to or higher than conventional animal proteins, making them a valuable source of bioavailable minerals that help prevent micronutrient deficiencies (Nirmala & Pramono, 2017). Together, these essential nutrients highlight the potential of sago worms as a functional and culturally significant food resource. Despite the growing recognition of sago worms as a nutrient-rich traditional food, there remains a notable lack of scientific research on processing methods that can support their application in modern nutritious food products. Most existing studies focus primarily on their nutritional composition, cultural significance, or ecological aspects, while systematic investigations on safe, standardized, and scalable processing techniques—such as drying, roasting, fermentation, defatting, or incorporation into composite flours—are largely absent (Rumpold & Schlüter, 2013; van Huis, 2013).This gap limits the ability of researchers and industry practitioners to optimize sago worm–based ingredients for functional, sensory, and safety attributes required in contemporary food manufacturing. Furthermore, the scarcity of studies on the effects of processing on nutrient stability, microbial safety, and shelf life constrains the development of fortified or value-added food products that could maximize their nutritional potential. Consequently, the limited availability of processing research poses a barrier to the broader utilization of sago worms in innovative, nutritionally enhanced food applications.

Therefore, the purpose of this research was to examine how various processing techniques influence the nutritional and functional quality of sago worms. The study focuses on assessing changes in key physicochemical parameters, as well as shifts in amino acid and essential fatty acid profiles, resulting from different processing conditions. Through this evaluation, the research was aimed to identify methods that best preserve or enhance the nutritional value of sago worms and provide guidance for developing safe and high-quality sago worm–based food products.

MATERIALS AND METHODS

Materials

This study characterized three types of sago worm samples: fresh, air-fried, and oven-dried. Fresh sago worms were sourced from a sago plantation center in Moramo, South Konawe, Southeast Sulawesi, Indonesia, and processed immediately upon arrival. The air-fried samples

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DOI: 10.5281/zenodo.23135554

were prepared using an air-frying unit operated at 100 °C for 15 minutes, while the oven-dried samples were produced by drying the worms in a hot-air oven at 60 °C for 6 hours. Following thermal treatment, all samples were finely ground to ensure homogeneity prior to subsequent chemical and instrumental analyses. All reagents and chemicals used in this study were of analytical grade to ensure accuracy and reliability of the measurements.

Chemical Analysis

Proximate composition—moisture, ash, crude protein (Kjeldahl), crude fat (Soxhlet), and carbohydrate by difference—was determined according to AOAC official methods and recent practical implementations in food analysis studies (AOAC, 2005; Djali et al., 2023). Amino acid profiles of samples were determined by high-performance liquid chromatography (HPLC) (Custodio-Mendoza et al., 2024). Essential fatty acids were analyzed by gas chromatography–mass spectrometry (GC–MS) (Guerrero-Esperanza et al., 2023). Together, these standardized and recently validated methods ensure robust quantification of the nutritional composition of sago worms for both compositional assessment and comparison across processing treatments.

Characterization with FTIR spectrophotometer

The functional groups present in the samples were characterized using Fourier Transform Infrared Spectroscopy (FTIR). For analysis, 2 mg of each sample was homogeneously mixed with 100 mg of spectroscopic-grade potassium bromide (KBr) and compressed into a pellet, which was then placed on the crystal cell of the FTIR spectrophotometer. Spectra were acquired in the mid-infrared range of 4000–500 cm^{-1} at ambient room temperature, enabling detection of characteristic functional group vibrations such as O–H, C–H, C=O, and amide bands associated with lipids, proteins, and other organic constituents (Colthup et al., 1990).

Scanning electron microscopy (SEM) analysis

The morphology and microstructure of the samples were examined using a scanning electron microscope (SEM) (COXEM, EM-30N; User Manual NS 4.1.5, Korea). Prior to imaging, the sample surfaces were coated with a thin layer of gold under vacuum using a sputter coater to enhance electrical conductivity and minimize charging. The coated samples were then photographed at 500× magnification to observe surface features and microstructural variations resulting from the different processing methods.

RESULTS AND DISCUSSION

Chemical Composition

The proximate chemical composition of the samples is shown in Table 1, and demonstrates clear effects of thermal processing on moisture reduction and subsequent nutrient concentration. The fresh sample exhibited a high moisture content (67.23%), which corresponded with lower proportions of fat (19.46%) and protein (7.60%), resulting in the lowest total energy value (224.98 kcal/100 g). This dilution effect is consistent with the well-established principle that high moisture content reduces the relative proportion of solids in biological materials (Rahman, 2020). In contrast, oven drying reduced moisture to 12.57%,

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DOI: 10.5281/zenodo.23135554

producing markedly higher concentrations of fat (57.60%) and protein (19.99%), as well as the greatest energy density (629.82 kcal/100 g). Such increases align with recent findings showing that dehydration methods significantly reduce moisture content and thereby increase the relative concentration of macronutrients in food matrices, as the removal of water concentrates the remaining solids and enhances nutrient density in dehydrated products (Moutia et al., 2024).

Table 1: Proximate Chemical Composition

Component	Unit	Fresh		Oven Dried		Air Fried	
		Average	std	Average	std	Average	std
Ash	%	0.85	0.01	1.97	0.03	1.89	0.04
Energy of fat	Kcal/100g	175.14	2.80	518.36	1.46	461.84	0.45
Total fat	%	19.46	0.31	57.60	0.16	51.32	0.05
Moisture	%	67.23	0.31	12.57	0.07	13.51	0.17
Total Energy	Kcal/100g	224.98	2.86	629.82	0.42	594.98	0.26
Carbohydrate (By Difference)	%	4.86	0.01	7.88	0.04	11.44	0.08
Protein	%	7.60	0.03	19.99	0.30	21.85	0.25

Air frying resulted in similar moisture reduction (13.51%), though the nutrient distribution differed from that of oven drying. The air-fried sample contained lower fat (51.32%) but higher protein (21.85%), yielding an energy value of 594.98 kcal/100 g. Rapid hot-air exposure during air frying is known to promote faster crust formation, partial lipid migration, and localized evaporation, which can reduce surface fat accumulation while concentrating protein within the tissue (Zhang et al., 2019; Tuta et al., 2020). Carbohydrate content, calculated by difference, increased in both processed samples, reflecting the relative enrichment of non-moisture, non-lipid, and non-protein components as water content decreased—a pattern commonly observed during drying of high-moisture foods (Fellows, 2009).

Overall, the results indicate that thermal processing—particularly oven drying and air frying—substantially alters the proximate composition of sago worms by reducing moisture and concentrating macronutrients. While oven drying produces the highest overall nutrient density, air frying yields a more protein-enriched composition with lower fat levels, illustrating how heat-transfer mechanisms and dehydration rates influence nutrient distribution and final nutritional quality.

Essential Fatty Acids Profiles

The essential fatty acid content of sago worms that have been processed using oven drying and air frying techniques, compared with fresh sago worms is shown in Figure 1. Thermal processing produced clear shifts in the fatty-acid composition of sago worms, primarily due to moisture loss and consequent lipid concentration effects. Across all treatments, oleic acid (omega-9) remained the predominant fatty acid. Its relative abundance increased markedly from the fresh sample (~8%) to the oven-dried (~26%) and air-fried (~23%) samples. This trend aligns with established evidence that dehydration increases the proportion of lipids on a dry-weight basis by reducing water content and concentrating hydrophobic components (Rahman, 2020; Nayak & Panda, 2023). The rise in oleic acid also suggests that

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DOI: 10.5281/zenodo.23135554

monounsaturated fatty acids are more thermally stable compared to polyunsaturated fatty acids, which are more prone to oxidative degradation during heating (Zhang et al., 2021).

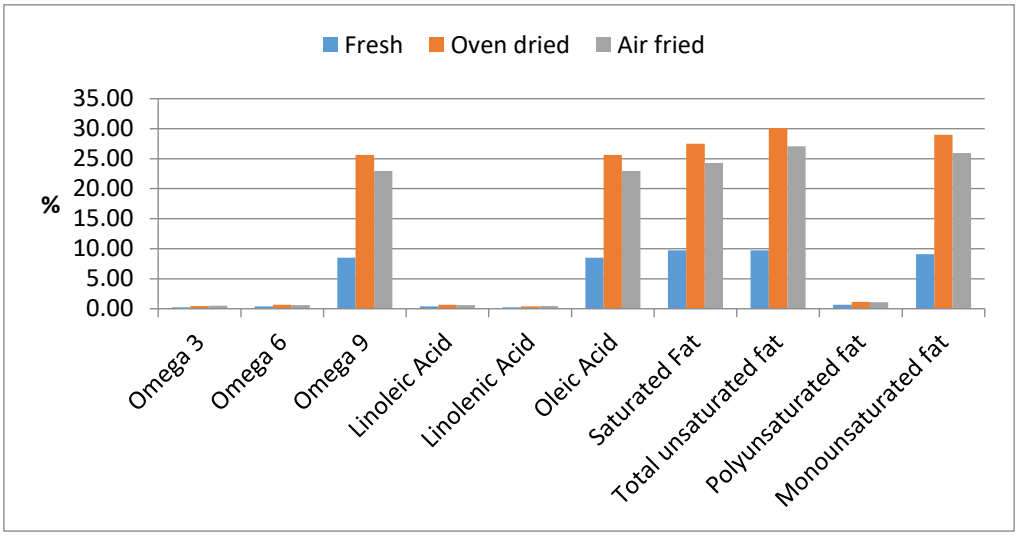

Figure 1: The Essential Fatty Acid Content of Sago Worms that have been Processed Using Oven Drying and Air Frying Techniques, Compared with Fresh Sago Worms

Similarly, total monounsaturated fat increased substantially following processing, with oven drying producing the highest values among treatments. Oven drying, characterized by longer exposure to moderate heat, often promotes uniform dehydration and lipid retention, resulting in elevated monounsaturated fat levels (Wang et al., 2025). Air frying, while also achieving significant moisture reduction, produced slightly lower monounsaturated fat levels than oven drying—likely due to the rapid heat transfer and turbulent air flow that can accelerate surface lipid oxidation (Téllez-Morales et al., 2024).

In contrast, polyunsaturated fatty acids (PUFAs) such as linoleic (omega-6) and linolenic acid (omega-3) remained relatively low in all samples. Although slight increases were observed in processed samples, the minimal change is consistent with the susceptibility of PUFAs to thermal degradation during high-temperature treatments (Choe & Min, 2007; de Oliveira, 2025). Oven drying resulted in the highest PUFA content among the treatments, suggesting that slower, controlled drying better preserves heat-sensitive fatty acids compared to the more aggressive heating profile of air frying. Overall, both thermal treatments increased the relative abundance of unsaturated fats, particularly omega-9 fatty acids, while oven drying exhibited the strongest concentration effect. These findings support existing evidence that processing conditions strongly influence lipid stability, oxidation behavior, and final fatty-acid profiles in high-fat biological materials (Zhuang et al., 2022).

Essential Amino Acid Profiles

Thermal processing produced clear shifts in the amino acid composition of sago worms, largely driven by moisture reduction and protein structural changes. Both oven drying and air frying resulted in higher concentrations of most amino acids compared with the fresh sample, as

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DOI: 10.5281/zenodo.23135554

shown in Figure 2, reflecting the well-established principle that dehydration concentrates protein on a dry-weight basis (Rahman, 2020; Nayak & Panda, 2023). This pattern was consistent for alanine, arginine, aspartic acid, glycine, glutamic acid, histidine, leucine, valine, phenylalanine, and several others. Among these, glutamic acid remained the most abundant amino acid across all treatments, confirming its known dominance in many insect protein matrices (Köhler et al., 2020).

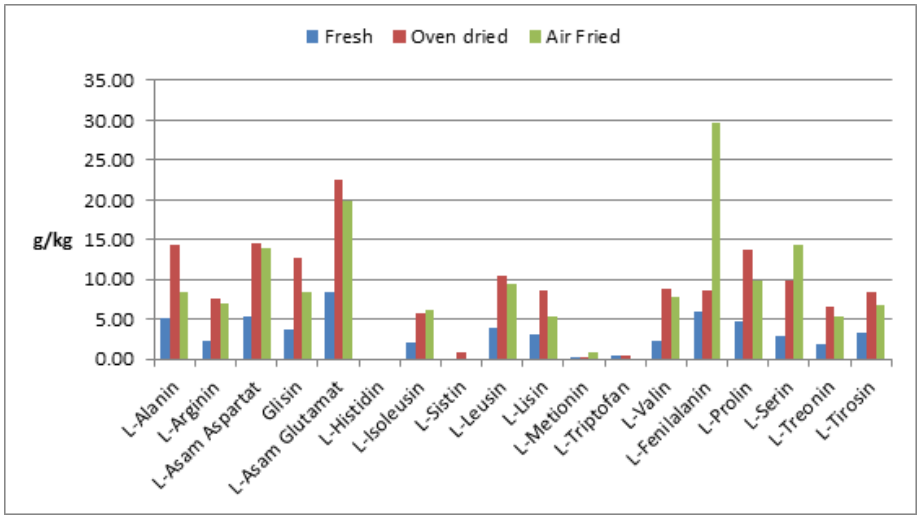

Figure 2: The Essential Amino Acid Content of Sago Worms that have been Processed Using Oven Drying and Air Frying Techniques, Compared with Fresh Sago Worms

A striking observation was the substantial increase in proline in the air-fried sample, reaching levels far higher than in the fresh or oven-dried treatments. This may be attributed to the rapid heat transfer and surface dehydration characteristic of air frying, which can promote the concentration of proline-rich structural proteins and accelerate partial unfolding or aggregation (Zhang et al., 2021; Rani et al., 2023). Essential amino acids such as leucine, isoleucine, valine, phenylalanine, and threonine also increased following thermal processing, with oven drying producing the most uniform enhancements. Slow, controlled oven drying conditions are known to preserve amino acid integrity more effectively than high-temperature, rapid-air processes (Siddiqui et al., 2024).In contrast, heat-sensitive amino acids—including lysine, methionine, and tryptophan—were slightly lower in the air-fried sample than in the oven-dried sample. These reductions align with previous findings that certain amino acids undergo degradation or participate in Maillard and oxidation reactions during high-temperature treatments (Choe & Min, 2007; Zhu et al., 2020). Thus, while both processing methods enhanced the overall amino acid concentration, oven drying yielded the most stable amino-acid profile, whereas air frying induced selective losses of heat-labile amino acids. Collectively, the results demonstrate that processing conditions strongly influence amino acid concentration and composition in sago worms. Moisture removal elevates overall amino-acid levels, while temperature intensity and heating rate determine the extent of protein denaturation, aggregation, and degradation—critical factors for evaluating nutritional quality in thermally processed edible insects.

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FTIR Analysis

The results of different sago worm's samples identification using the FTIR spectrum as in Table 2 and Figure 3 shows that all samples have almost identical spectrum profiles. All three spectra exhibit relatively similar absorption patterns, with variations primarily observed in the intensity of specific wavenumber regions. The overall similarity in spectral profiles indicates that the three samples share a fundamentally homogeneous chemical composition, despite being subjected to different processing treatments. However, the thermal treatments appear to influence the relative abundance and intensity of certain functional groups, suggesting alterations in molecular structure such as partial lipid oxidation, protein denaturation, or changes in moisture-associated bonds. These differences in peak intensities reflect shifts in the chemical contributions of lipids, proteins, and other constituents, while the consistent spectral pattern confirms the preservation of the core chemical framework across all samples.

Sago worms are known to contain high levels of lipids—primarily triglycerides and unsaturated fatty acids, with omega-9 as a dominant component—as well as substantial amounts of protein composed of various amino acids, particularly glutamic acid and phenylalanine. Given this compositional profile, the interpretation of the FTIR spectra is focused on identifying the major functional groups that represent these two key constituents. In the lipid fraction, characteristic absorption bands associated with C–H stretching, carbonyl (C=O) groups of triglycerides, and unsaturated C=C bonds are expected to appear prominently. Meanwhile, the protein component is typically indicated by amide I and amide II bands, which correspond to C=O stretching and N–H bending vibrations, respectively, reflecting the presence of peptide bonds and amino acid structures. Together, these spectral features allow for a more precise understanding of the molecular composition of sago worms and the impact of processing on their chemical structure.

Table 2: Functional Group of Sago Worms Processed Under Different Conditions (Fresh, Air Fried, and Oven Dried)

No.	Wavenumber (cm^{-1})	Functional Group	Interpretation
1	3500–2500	O–H stretching	Very broad, strong band caused by extensive H-bonding between fatty-acid carboxyl groups and water. Most dominant in the fresh sample due to high moisture content, indicating the polar nature of natural lipid tissues.
2	~3300	N–H stretching	Narrow to medium band from amine or amide groups in proteins/amino acids. Appears as a small shoulder on the O–H band. Intensity decreases in Air Fried and Oven Dried due to protein denaturation.
3	3000–2800	C–H stretching (sp^3)	Strong, sharp peaks characteristic of alkyl chains in saturated and unsaturated fatty acids. Highest intensity in Oven Dried, indicating increased lipid concentration after moisture reduction.
4	1740	C=O stretching (ester)	Strong, sharp peak associated with ester carbonyl groups in triglycerides. Highest in Oven Dried due to dominant lipid content; weaker in Fresh due to water interference.
5	1650–1630	Amide I (C=O stretching)	Medium, sharp band from carbonyl vibrations in peptide bonds. Clearly visible in Fresh, indicating intact protein

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DOI: 10.5281/zenodo.23135554

			structure. Lower intensities in Air Fried and Oven Dried suggest thermal modification of secondary protein structures.
6	1620–1600	C=C stretching (alkenes)	Medium to weak band indicating the presence of double bonds in unsaturated fatty acids (e.g., oleic acid/omega-9). Serves as a marker of lipid unsaturation.
7	1575–1500	Amide II (N–H bending and C–N stretching)	Medium band associated with protein vibrational modes. Reduced intensity in Air Fried and Oven Dried indicates protein denaturation due to heat treatment.
8	1300–1000	C–O stretching (ester) and C–N stretching (amide)	Strong, complex band representing overlapping ester (lipid) and amide (protein) vibrations. Strongest in Oven Dried due to high lipid concentration. Confirms coexistence of lipid and protein components.

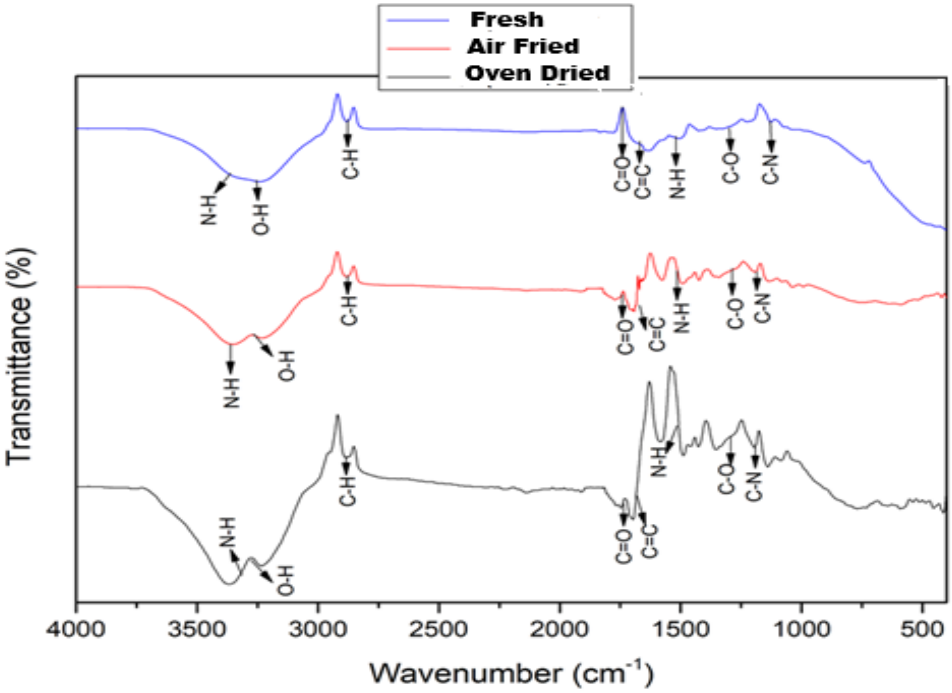

Figure 3: FTIR Spectrum of Sago Worms Processed Under Different Conditions (Fresh, Air Fried, and Oven Dried)

Interpretation of the FTIR spectra shows that all three samples contain the major functional groups O–H, C–H, C=O (from ester and amide bonds), C=C, and C–N. These functional groups correspond to the primary biochemical constituents of sago worms, namely lipids—particularly triglycerides and unsaturated fatty acids such as omega-9—and proteins composed of amino acids such as glutamic acid and phenylalanine. Comparisons of peak intensities among the samples indicated compositional differences resulting from thermal treatments. Fresh sample contained highest moisture and protein, with the most intact native structure. Air fried sample contained a balanced lipid and protein content, with mild protein denaturation. Then, oven dried sample contained the highest relative lipid content due to moisture reduction and concentration

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of fat components. Overall, the FTIR results confirm that sago worms are a natural source of high-quality lipids and proteins, with omega-9 fatty acids, glutamic acid, and phenylalanine serving as dominant chemical markers that characterize their nutritional composition.

Scanning Electron Microscopy (SEM) Analysis

Observation of the morphology of sago flour–sago worm mixtures using Scanning Electron Microscopy (SEM) provides a clear depiction of the microstructural changes resulting from different processing treatments, which can be seen in Figure 4. The three samples—mixtures prepared with fresh sago worms, air-fried worms, and oven-dried worms—exhibited distinctly different surface characteristics, reflecting the influence of moisture content, protein denaturation, and alterations in internal components during heating. These microstructural variations highlight how thermal processing affects the integrity, distribution, and interaction of starch granules, proteins, and lipids within the composite matrix, ultimately shaping the functional and textural properties of the final material.

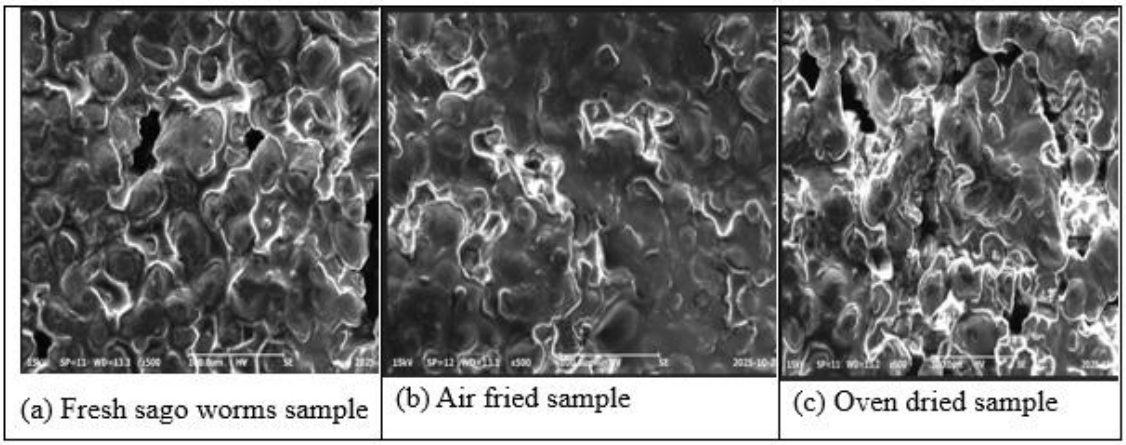

Figure 4: Scanning Electron Microscopy (SEM) Micrograph Profiles of (A) Fresh, (B) Air Fried and (C) Oven Dried Samples

The SEM image in Figure 4a shows the least homogeneous structure among all treatments. Large, irregular agglomerates are visible, accompanied by naturally formed large pores. These pores indicate voids created by the evaporation of moisture from the fresh sago worms during sample preparation, a phenomenon commonly observed in high-moisture biological tissues (Rahman, 2020). The rough surface morphology suggests that the sago worm tissues largely retain their native structure, with minimal alteration to the protein and lipid networks, consistent with behavior seen in unheated animal-derived matrices (Bolumar et al., 2021). The high moisture content in the fresh sample leads to unstable clumping when mixed with sago flour, preventing the formation of a compact matrix and resulting in weak interactions between components. This agrees with established principles stating that fresh, protein- and lipid-rich materials exhibit low binding capacity and poor adhesion prior to thermal denaturation because the native protein structure has not yet unfolded to expose reactive binding sites (Schmid et al., 2014).

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The SEM image in Figure 4b reveals a much more homogeneous structure compared with the fresh sample. The air-frying process, which operates through rapid circulation of hot air at elevated temperatures, promotes fast and uniform moisture removal, resulting in a denser and more compact surface matrix (Téllez-Morales et al., 2024). The fine cracks observed in the micrograph indicate shrinkage and volume reduction of the sago worm biomass following intensive dehydration, a phenomenon commonly reported in high-temperature drying of protein–lipid materials (Rahman, 2020). In addition, the increased structural density in the air-fried sample is associated with more extensive protein denaturation and lipid softening or partial melting relative to other treatments. Coagulated proteins and thermally softened lipids subsequently re-solidify upon cooling, producing small, uniform agglomerates (Yuly et al., 2017). This microstructural pattern reflects improved mixing quality and stronger interactions between sago flour components and the treated sago worm tissues, consistent with the behavior of heat-modified food matrices where dehydration enhances adhesion and interparticle bonding (Yadollahinia & Jahangiri, 2009).

Figure 4c displays a surface morphology that is intermediate between the fresh and air-fried samples: agglomerates are larger and denser than in air fried but more uniform than in the fresh sample. Oven drying proceeds more slowly than air-frying, causing a gradual loss of moisture that typically yields a hardened surface while partially preserving elements of the original tissue architecture (Sultana et al., 2024). The presence of moderate-sized pores and a few localized cracks—rather than the fine, widespread fissuring seen after rapid dehydration—reflects this slower dehydration regime and is consistent with pore-formation mechanisms during conventional hot-air drying (Aghajanzadeh et al., 2024). Because the thermal and mass-transfer intensities are lower than in air-frying, protein denaturation and surface restructuring are less pronounced; consequently, some native protein–lipid organization can remain, while partial melting and resolidification of lipids can produce the larger agglomerates observed (Ye et al., 2024). Overall, the SEM pattern in Figure 4c indicates that oven drying induces structural consolidation and localized lipid coalescence but does not produce the same degree of protein coagulation and microstructural densification characteristic of high-rate air-frying.

The morphological differences observed among the treatments have direct implications for the characteristics of the final product, particularly in terms of texture, stability, and potential application in food formulations. The homogeneous and compact structure produced by air frying suggests a greater ability to form physically stable products, making this treatment suitable for applications that require firmness and structural integrity. In contrast, the highly porous structure of the fresh sample may benefit products that rely on high absorption capacity, such as fillers or moisture-retaining ingredients, although its mechanical stability remains limited. Oven drying provides an intermediate morphology, balancing porosity and density, which may be advantageous when a moderate texture—neither too hard nor too fragile—is desired while still maintaining acceptable product stability. These structural distinctions highlight the importance of selecting appropriate processing methods to achieve targeted functional properties in sago worm–based food products.

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CONCLUSION

Thermal processing—particularly oven drying and air frying—significantly alters the nutritional composition, chemical structure, and microstructural characteristics of sago worms. Moisture reduction markedly increased protein, lipid, and energy densities, while essential fatty-acid and amino-acid profiles were enhanced, especially monounsaturated fatty acids (omega-9) and glutamic acid. FTIR confirmed consistent core chemical frameworks with treatment-dependent shifts in functional-group intensities, and SEM revealed distinct structural transformations that influence potential textural applications. The findings advance knowledge by showing how specific thermal conditions modulate nutrient concentration, protein stability, lipid behavior, and microstructure in edible insects. The enhanced protein and omega-9 content in processed sago worms supports their use in high-protein products, while the defined microstructures suggest suitability for snacks, flours, and composite ingredients. The study therefore contributes to the development of sustainable, functional foods derived from culturally significant edible insects

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This research was funded by the Directorate of Research and Community Services, Directorate General of Research and Development, Ministry of Higher Education, Science and Technology, Republic of Indonesia, under the scheme of Regular Fundamental Research 2025. We extend our sincere gratitude for their funding support.

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DOI: 10.5281/zenodo.23135554

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