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Physicochemical properties and glutamic acid content of foam-mat dried peanut worm (*Siphonosoma australe*) powder prepared using different protein–xanthan gum foaming systems

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ABSTRACT

The increasing demand for natural umami ingredients has encouraged the exploration of alternative raw materials and drying technologies. This study evaluated the effects of different protein–polysaccharide foaming systems on the physicochemical properties and glutamic acid content of foam-mat dried peanut worm (*Siphonosoma australe*) powder. Peanut worm extract was encapsulated using composite wall materials and combined with different foaming systems consisting of egg white powder, egg white powder–xanthan gum (EWP–XG), soy protein isolate–xanthan gum, and sodium caseinate–xanthan gum (SC–XG) before foam-mat drying. The different foaming systems significantly affected several physicochemical and functional properties of the resulting powders. Among the formulations, EWP–XG exhibited favorable characteristics, including higher foam expansion and stability, smaller particle size, superior rehydration characteristics, lower moisture content and hygroscopicity, and a brighter color. SC–XG produced the highest powder yield and the numerically highest glutamic acid content, which did not differ significantly from that of EWP–XG, but showed poorer dispersibility and a longer dissolution time than EWP–XG. Blank formulation analysis showed that the formulation ingredients themselves contained measurable background glutamic acid. Overall, the results demonstrate that different protein–polysaccharide foaming systems produce distinct physicochemical and functional characteristics in foam-mat dried peanut worm powder and influence the glutamic acid content of the resulting products.

1. INTRODUCTION

The demand for natural umami ingredients has increased in parallel with growing consumer interest in clean-label foods and natural flavor-enhancing ingredients [1,2]. Umami taste is primarily attributed to free glutamic acid, which enhances palatability and exhibits synergistic effects in taste perception, enabling salt reduction in food formulations [3,4]. This trend has driven the exploration of sustainable and functional natural sources of umami.

Various biological resources, including seaweeds, seafood by-products, and mushrooms, have been identified as potential umami sources [5–8]. Among these, peanut worm (*Siphonosoma australe*) has gained attention due to its high content of free amino acids, particularly glutamic acid, indicating that peanut worm is a promising natural source of glutamic acid for food applications [9,10]. Previous studies have demonstrated that spray-drying-based encapsulation improves the stability of bioactive compounds and enhances the physical properties of peanut worm extract [11]. However, its industrial application remains limited by high energy demand, operational complexity, and the risk of thermal degradation of heat-sensitive compounds [12,13].

Foam-mat drying (FMD) has been reported as a simple drying approach with potential advantages in powder production due to foam formation, which can increase exposed surface area and facilitate moisture removal during drying. Previous studies have reported that FMD can produce powders with desirable solubility, storage stability, and reduced thermal degradation compared with some conventional drying approaches [14–16]. However, its performance is strongly influenced by foam stability, which depends on the interfacial properties of foaming agents. The incorporation of polysaccharides such as xanthan gum can further enhance foam stability by increasing viscosity and modifying the rheological characteristics of the foaming system [17]. These changes may influence foam structure development during drying and subsequently affect the physicochemical properties of the resulting powder [18].

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The foaming performance of proteins is closely associated with their molecular structure and interfacial behavior. Egg white proteins, predominantly ovalbumin, possess flexible globular structures that readily adsorb and partially unfold at the air–water interface, forming cohesive viscoelastic films that promote excellent foaming and foam stability [19–21]. In contrast, soy protein isolate consists mainly of the globular storage proteins glycinin and β-conglycinin, whose larger molecular assemblies generally exhibit slower adsorption and structural rearrangement at the interface [17,22]. Sodium caseinate differs from egg white and soy proteins in its interfacial and colloidal behavior. Recent studies have shown that sodium caseinate can form complexes with xanthan gum through protein–polysaccharide interactions, and that the resulting interfacial and rheological properties depend on factors such as the protein-to-polysaccharide ratio and formulation conditions [23]. These characteristics may influence foam formation and foam stability.

To date, limited information is available regarding the comparative effects of different protein-based foaming systems, particularly in combination with xanthan gum, on the physicochemical and functional properties of foam-mat dried marine-derived powders containing relatively high levels of glutamic acid. Therefore, this study aimed to evaluate the effects of different protein–polysaccharide foaming systems consisting of egg white powder, soy protein isolate, sodium caseinate, and xanthan gum on the physicochemical properties, functional characteristics, and glutamic acid content of peanut worm (*Siphonosoma australe*) powder produced by foam-mat drying. The findings provide insights into the selection of suitable foaming systems for improving the quality characteristics of marine-derived powders with high glutamic acid content.

2. MATERIALS AND METHODS

2.1. Materials

The primary raw material used in this study was peanut worm, obtained from local fishermen at Teronipa Beach (Southeast Sulawesi, Indonesia). The encapsulating agents included maltodextrin (Lihua Starch, China), gum arabic (Ingredion, Thailand), and β-cyclodextrin (Landor Trading Company, Thailand). Foaming agents consisted of egg white powder (Pristine Nutrition, Indonesia; 80% protein), soy protein isolate (Raja Rizki Sejahtera, Indonesia; 90% protein), sodium caseinate (Marvellous Chemical, Indonesia; 90% protein), and xanthan gum (Deosen Biochemical, China). All analytical procedures were performed using analytical-grade reagents obtained from Sigma-Aldrich (USA).

2.2. Peanut Worm Extraction Process

Cleaned and dried peanut worm samples were ground using a disc mill (Agrowindo-FFC23, Indonesia) and sieved to obtain a uniform powder (60 mesh). A total of 100 g of powder was extracted with 3% (w/v) citric acid at a material-to-solvent ratio of 1:8 (w/v). The extraction was carried out under refrigerated conditions (Panasonic, Indonesia) at 4°C for 36 hours. The mixture was then filtered using Whatman filter paper to remove solid residues. The filtrate was centrifuged (PLC-05, Germany) at 4,000 rpm for 10 minutes at 10°C to eliminate remaining suspended particles. The pH was adjusted to 7.0 ± 0.1 using 1 N NaOH. Subsequently, the filtrate was concentrated using a rotary evaporator (Biobase RE-301, China) at 50°C for 30 minutes. The resulting extract was used for subsequent analyses [10].

2.3. Peanut Worm Encapsulation Process

The wall-material composition used in the present study was adopted from a formulation previously applied in our published study on the microencapsulation of peanut worm (*Siphonosoma australe*) extract [11]. A total of 40 g of wall materials, consisting of maltodextrin, gum arabic, and β-cyclodextrin at a ratio of 49:49:2 (w/w), corresponding to 19.6, 19.6, and 0.8 g, respectively, was dissolved in 100 ml of distilled water and homogenized at 3,000 rpm for 30 minutes. In this composite wall system, maltodextrin was used primarily as a carrier and drying aid, gum arabic as a film-forming and emulsifying material, and β-cyclodextrin as a supplementary encapsulating material. The wall-material composition was kept constant across all treatments because the experimental factor investigated in the present study was the protein–xanthan gum foaming system rather than the type or proportion of the wall materials; therefore, this formulation was adopted from the previous study [11] and was not optimized in the present experiment. Subsequently, 100 ml of peanut worm extract was added to obtain a mixture with approximately 45% (w/w) total solids, followed by further homogenization at the same speed for 30 minutes. Foaming agents (Table 1), totaling 4 g, were then added according to each treatment, and the mixture was whipped at 1,500 rpm for 5 minutes to form a stable foam. The foam was evenly spread onto non-perforated trays (45 × 45 cm) at a thickness of approximately 1 mm and dried in a cabinet dryer (Maksindo KD-35AS, Indonesia) at 60°C for 6 hours. The resulting dried foam sheets were ground using a mill (FOMAC Miller Machine FGD-Z500, Indonesia) to produce peanut worm powder (PWP), which was used for subsequent analyses [11,18].

2.4. Foaming Properties Analysis

The foaming properties evaluated in this study included foam expansion and foam stability [16]. Foam expansion refers to the ability of a foaming agent to incorporate air into the peanut worm extract solution, leading to foam formation. Foam expansion (%) was calculated based on the increase in volume after whipping, defined as the difference between the final foam volume (cm^3) and the initial solution volume (cm^3), divided by the initial volume and expressed as a percentage. Foam stability was determined by transferring the formed foam into a 50 ml volumetric flask and allowing it to stand at 27°C ± 2°C for 30 minutes. After this period, the remaining foam volume was measured and expressed as foam stability (%).

2.5. Morphological Structure and Particle Size Analysis

The morphological structure of PWP was examined using scanning electron microscopy (SEM) (JEOL JSM-6510LA, JEOL Ltd., Japan). Prior to analysis, the powder samples were sputter-coated with a thin layer of gold to improve electrical conductivity. Micrographs were acquired at an accelerating voltage of 10 kV with a magnification of 500× (scale bar = 50 μm). SEM images were captured from at least five

Table 1. Composition of foaming agent.

Code	Foaming agent (%)			
	EWP	SPI	SC	XG
EWP	100	0	0	0
EWP–XG	90	0	0	10
SPI–XG	0	90	0	10
SC–XG	0	0	90	10

EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; SC–XG, Sodium caseinate and xanthan gum.

randomly selected fields for each treatment. Particle size distribution was determined using a laser diffraction particle size analyzer (Labron LLPA-C10, United Kingdom) with distilled water as the dispersing medium. Measurements were performed according to the instrument's standard operating procedure and reported as the volume-weighted mean diameter, D [3,4]. The refractive-index and obscuration settings were not recorded separately in the laboratory worksheet and therefore could not be reliably reconstructed retrospectively. Measurements were performed in quintuplicate, and the results were reported as mean ± standard deviation [11].

2.6. Rehydration Properties Analysis

The rehydration properties of PWP, including dispersibility, Dispersion time, and solubility, were evaluated. Dispersibility was determined by dispersing 1 g of PWP (WS) in 10 ml of distilled water in a 50 ml beaker, followed by continuous stirring for 30 minutes until complete dispersion was achieved without sediment or agglomerate formation. The suspension was filtered through a 200-mesh sieve, and the filtrate was dried to a constant weight (WF). Dispersibility was calculated using an equation adapted from a previous study [16].

$$\text{Dispersibility (\%)} = \frac{\text{WF(g)}}{\text{WS(g)}} \times 100 \quad [1]$$

Dissolution time was measured by dissolving 1 g of PWP in 10 ml of distilled water under continuous stirring using a magnetic stirrer (B-ONE LMS-6-1500, Indonesia), and the time required for complete dispersion without visible agglomerates was recorded [16]. Solubility was determined by dispersing 1 g of PWP in 100 ml of distilled water in a 250 ml beaker, followed by stirring at room temperature for 30 minutes and centrifugation at 3,000 rpm for 5 minutes. The supernatant was dried to constant weight, and solubility (%) was calculated as the ratio of dissolved solids to initial sample mass [24].

2.7. Moisture Content and Water Activity

The moisture content of PWP was determined using a moisture analyzer (Shimadzu MOC63u, Japan) until a constant weight was reached according to the manufacturer's procedure. Moisture content was expressed on a wet basis as the percentage of mass lost during drying relative to the initial sample mass. Water activity (a_w) was measured using an aw analyzer (Rotronic HygroPalm HP23-AW-A, Switzerland) at 27°C. Prior to analysis, the samples were placed in sealed containers to ensure a closed headspace, and aw values were recorded after the readings had stabilized.

2.8. Hygroscopicity

The hygroscopicity of PWP was determined by weighing 1 g of sample and placing it in an open container, which was then stored in a sealed desiccator maintained at 75.5% relative humidity, generated using a saturated NaCl solution. The samples were kept at 27°C ± 2°C for 7 days under dark conditions. After the storage period, the samples were reweighed to determine the mass increase due to moisture uptake. Hygroscopicity was expressed as the percentage of absorbed water relative to the initial sample weight [24].

2.9. Flow Properties

The flow properties of PWP were evaluated by determining bulk density (BD), tapped density (TD), compressibility index (CI), and Hausner ratio (HR). Bulk density was measured by filling a 100 ml graduated cylinder (Merck, Germany) with the sample to a volume of 25 ml without compaction. The sample was then weighed, and BD was calculated as the ratio of sample mass to the occupied volume, expressed in g/cm³. For tapped density determination, the same graduated cylinder containing the sample was tapped 10 times under consistent conditions, after which the final compacted volume was recorded. TD was calculated as the ratio of sample mass to the final tapped volume and expressed in g/cm³. CI and HR were calculated from BD and TD values according to previously reported equations [7].

$$\text{CI (\%)} = \frac{\text{(TD-BD)}}{\text{TD}} \times 100 \quad [2]$$

$$\text{HR} = \frac{\text{TD}}{\text{BD}} \quad [3]$$

2.10. Yield and Chemical Properties

The yield of FMD-produced PWP was determined by comparing the mass of the final powder obtained with the total solids in the initial drying formulation, including peanut worm extract solids, wall materials, and foaming agents and expressed as a percentage. The glutamic acid content of the samples was determined using an L-glutamic acid assay kit (Megazyme) according to the manufacturer's instructions. Absorbance was measured using a UV-Vis spectrophotometer (Shimadzu UV-Vis 1601, Japan) at 492 nm [11]. Protein content was determined using the Lowry method with bovine serum albumin as the standard. Absorbance was measured using a UV-Vis spectrophotometer (Shimadzu UV-Vis 1601, Japan) at 660 nm [10]. The pH of the samples was measured using a pH meter (Hanna HI 2211, Italy). Prior to measurement, the instrument was calibrated with standard buffer solutions, and readings were recorded after stabilization.

2.11. Color Profile

The color profile of PWP was measured using a chromameter (Konica Minolta, Japan) based on the CIELab color system, including L*, a*, and b* parameters. The L* value indicates lightness (0 = black, 100 = white), the a* value represents the red (+) to green (−) axis, and the b* value represents the yellow (+) to blue (−) axis. In addition, the whiteness index (WI) of PWP was calculated from L*, a*, and b* values using a commonly reported equation [11].

$$\text{WI} = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad [4]$$

2.12. Statistical Analysis

Each formulation was independently prepared in five separate batches (n = 5), and one value from each independent batch was used for statistical analysis. The results are presented as the mean plus or minus the standard deviation. Statistical analyses were carried out using SPSS software (version 20.0; IBM Corp., Armonk, NY, USA). One-way analysis of variance was applied to determine significant differences among the samples. When significant differences were detected ($p < 0.05$), mean comparisons were performed using Duncan's multiple range test (DMRT).

3. RESULTS AND DISCUSSION

3.1. Foam Properties

The results showed that the type of foaming system significantly influenced foam expansion and foam stability (Table 2). The highest

foam expansion was recorded for the egg white powder–xanthan gum (EWP–XG) system (43.67%), followed by SPI–XG (38.03%), sodium caseinate–xanthan gum (SC–XG) (35.37%), and egg white powder (EWP) (33.04%). A similar trend was observed for foam stability, with EWP–XG exhibiting the highest value (94.28%), followed by SPI–XG (88.30%), SC–XG (83.29%), and EWP (78.37%). Foam expansion of approximately 35% has been reported as the minimum required to produce a stable foam structure suitable for foam-mat drying [16]. Among the tested formulations, EWP–XG, soy protein isolate–xanthan gum (SPI–XG), and SC–XG exhibited higher foam expansion and foam stability values than EWP. Higher foam expansion reduces foam density and increases the exposed surface area, thereby facilitating heat transfer and moisture removal during drying [25]. In contrast, the lower foam expansion observed in EWP may produce a denser foam structure that is more susceptible to collapse during drying [26,27]. EWP without xanthan gum exhibited a relatively limited ability to maintain a stable foam structure. Previous studies have shown that xanthan gum can increase the viscosity of the continuous phase and modify protein–polysaccharide interactions, thereby improving foam stability [19,21,28]. These mechanisms may help explain the differences observed among the tested protein–polysaccharide formulations, although the present experimental design does not allow the independent effect of xanthan gum to be isolated for each protein source.

Differences among the xanthan gum-containing formulations may also be associated with the intrinsic properties of the proteins. Egg white proteins, particularly ovalbumin, readily adsorb and partially unfold at the air–water interface, forming cohesive and elastic interfacial films that effectively stabilize air bubbles. This characteristic likely contributed to the superior foam expansion and stability observed in the EWP–XG system. In contrast, soy protein isolate is composed mainly of the globular proteins glycinin and β-conglycinin, which generally require greater conformational rearrangement before forming stable interfacial films. This behavior may explain the intermediate foam properties obtained with SPI–XG. The behavior of the SC–XG system may be related to interactions between sodium caseinate and xanthan gum, which can modify the interfacial and rheological properties of the protein–polysaccharide system [23]. In the present study, SC–XG exhibited higher foam expansion and foam stability values than EWP, although its values remained lower than those of EWP–XG. These interpretations are consistent with previous reports showing formulation-dependent differences in foam and powder characteristics [28–30]. High foam stability is considered an important prerequisite for successful foam-mat drying because it influences the structural integrity of the drying foam and may subsequently affect particle morphology, rehydration behavior, moisture characteristics, hygroscopicity, and powder flow properties.

Table 2. Foaming properties of peanut worm extract with different foaming agents.

Foaming agent	Foam expansion (%)	Foam stability (%)
EWP	33.04 ± 0.63^{a}	78.37 ± 0.28^{a}
EWP–XG	43.67 ± 0.22^{d}	94.28 ± 0.44^{d}
SPI–XG	38.03 ± 0.18^{c}	88.30 ± 0.63^{c}
SC–XG	35.37 ± 0.04^{b}	83.29 ± 0.52^{b}

Values are presented as means ± standard deviations (n = 5).

Values in the same column with the same superscript are not significantly different (p > 0.05).

EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; SC–XG, Sodium caseinate and xanthan gum.

3.2. Morphological Structure and Particle Size

The morphological characteristics of the powders are presented in Figure 1, while the average particle size is shown in Figure 2. SEM observations revealed that all formulations exhibited irregular particle morphology with rough surfaces and varying degrees of agglomeration, which are typical characteristics of foam-mat dried powders. Nevertheless, noticeable differences in particle compactness, surface integrity, and particle size were observed among the different protein–polysaccharide foaming systems, indicating that formulation composition influenced the structural characteristics of the final powders. The EWP formulation produced relatively large particles (50.37 μm) with comparatively smooth surfaces but visible surface cracks. This morphology was consistent with the lower foam expansion and foam stability observed for EWP (Table 2), suggesting that the less stable foam structure may have contributed to the formation of larger particles and visible surface cracks during drying. Compared with EWP, the EWP–XG formulation produced significantly smaller particles (34.58 μm) with a more compact and uniform morphology and fewer visible cracks. These observations were consistent with the superior foam properties of the EWP–XG system discussed above and suggest that improved foam stability promoted a more homogeneous powder structure during drying.

The SPI–XG formulation exhibited an intermediate particle size (42.04 μm) with moderate agglomeration, and its particles were less uniform than those of EWP–XG. This observation was consistent with the intermediate foam properties of SPI–XG and may reflect the different interfacial behavior of soy proteins compared with egg white proteins [31]. In contrast, SC–XG exhibited the largest particle size (83.92 μm) together with a rough and highly agglomerated structure. The larger particles and denser morphology were consistent with its relatively lower foam expansion and higher powder yield, suggesting that differences in the foaming characteristics of the protein systems influenced the structural organization of the resulting powder [32]. The denser structure of SC–XG may also explain its comparatively lower rehydration performance.

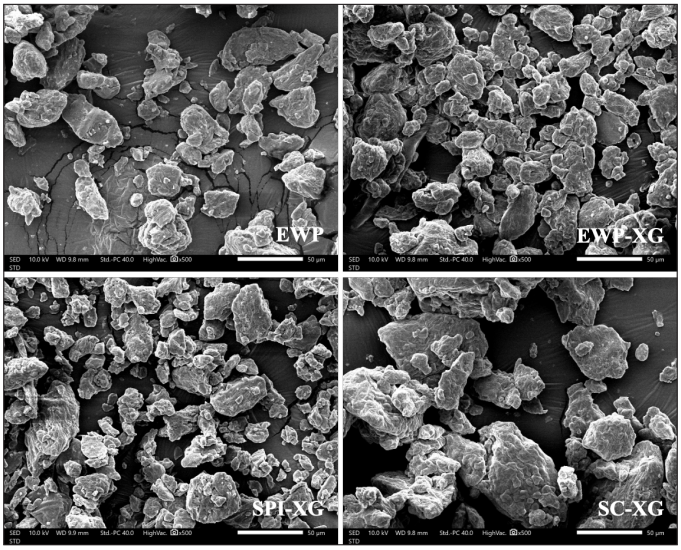

Figure 1. Scanning electron micrograph of foam-mat dried peanut worm powder with different foaming agents. Egg white powder (EWP), a mixture of EWP–xanthan gum (EWP–XG), soy protein isolate–XG (SPI–XG), and sodium caseinate–XG (SC–XG). Micrographs were captured at a magnification of 500× with a scale bar of 50 μm.

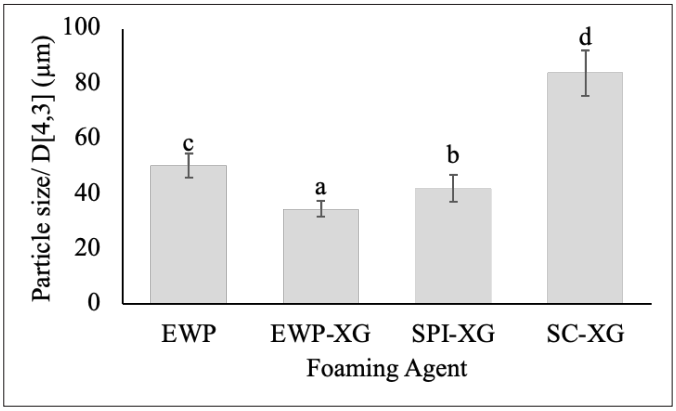

Figure 2. Average particle size of foam-mat dried peanut worm powder with different foaming agents. Egg white powder (EWP), a mixture of EWP–xanthan gum (EWP–XG), soy protein isolate–XG (SPI–XG), and sodium caseinate–XG (SC–XG). Values are mean ± SD (n = 5). Different letters indicate significant differences among formulations (DMRT, $p < 0.05$).

Table 3. Rehydration properties of foam-mat dried peanut worm powder with different foaming agents.

Foaming Agent	Dispersibility (%)	Dissolution Time (s)	Solubility (%)
EWP	82.99 ± 0.52^{b}	106.42 ± 3.94^{c}	91.03 ± 0.94^{a}
EWP–XG	93.28 ± 0.73^{d}	68.36 ± 2.77^{a}	96.38 ± 0.11^{c}
SPI–XG	89.47 ± 0.14^{c}	79.21 ± 4.18^{b}	95.77 ± 0.27^{c}
SC–XG	78.81 ± 0.78^{a}	121.34 ± 5.92^{d}	93.29 ± 0.53^{b}

Values are presented as means ± standard deviations (n = 5).

Values in the same column with the same superscript are not significantly different ($p > 0.05$).

EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; SC–XG, Sodium caseinate and xanthan gum.

3.3. Rehydration Properties

Most powdered food products are intended for rehydration; therefore, desirable characteristics include rapid wetting, dispersion, dissolution, and minimal agglomeration during reconstitution [26]. In the present study, EWP–XG exhibited the highest dispersibility (93.28%), the shortest dissolution time (68.36 s), and the highest solubility (96.38%) (Table 3). SPI–XG showed the second-highest dispersibility and the second-shortest dissolution time. Its solubility did not differ significantly from that of EWP–XG. In contrast, SC–XG exhibited the lowest dispersibility and the longest dissolution time, although its solubility (93.29%) remained higher than that of EWP (91.03%). Rehydration behavior differed among the tested protein–polysaccharide formulations and depended on the specific rehydration parameter evaluated. EWP–XG and SPI–XG showed more favorable overall rehydration characteristics than SC–XG, whereas the response of SC–XG differed among the measured parameters. These observations were consistent with the particle morphology and particle-size distribution discussed in Section 3.2, where EWP–XG produced smaller and more homogeneous particles. Previous studies have shown that smaller particle size and greater powder porosity can facilitate water penetration and improve powder dispersion and dissolution during rehydration [11,14,15].

The relatively poor dispersibility and prolonged dissolution time of SC–XG were consistent with its larger particle size and more agglomerated morphology. These structural characteristics may have restricted water penetration into the particles, thereby slowing powder dispersion and dissolution during rehydration. Nevertheless, the higher solubility of SC–XG compared with EWP indicates that dispersibility, dissolution time, and solubility should not be interpreted as interchangeable measures because each reflects a different aspect of powder reconstitution behavior. Previous studies have similarly reported that powder microstructure is an important determinant of hydration behavior in dried food powders [16,33]. Overall, the rehydration properties observed in this study were associated with differences in foam characteristics, particle morphology, and particle size. Formulations with higher foam expansion and foam stability, particularly EWP–XG, generally produced more homogeneous powders with more favorable rehydration behavior. However, the differences among formulations varied according to the specific rehydration parameter, indicating that the choice of protein–polysaccharide foaming system influenced multiple aspects of powder reconstitution rather than producing a single uniform ranking across all rehydration properties.

Table 4. Moisture content, a_w, and hygroscopicity of foam-mat dried peanut worm powder with different foaming agents.

Foaming Agent	Moisture Content (%)	a_w	Hygroscopicity (%)
EWP	5.97 ± 0.23^{b}	0.38 ± 0.14^{a}	13.27 ± 0.62^{c}
EWP–XG	5.02 ± 0.61^{a}	0.28 ± 0.08^{a}	10.62 ± 0.54^{a}
SPI–XG	5.48 ± 0.74^{ab}	0.33 ± 0.23^{a}	11.94 ± 0.84^{b}
SC–XG	6.01 ± 0.28^{b}	0.41 ± 0.17^{a}	14.02 ± 0.35^{c}

Values are presented as means ± standard deviations (n = 5).

Values in the same column with the same superscript are not significantly different ($p > 0.05$).

EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; SC–XG, Sodium caseinate and xanthan gum.

3.4. Moisture Content and Water Activity (a_w)

Moisture content differed significantly among the formulations (p = 0.025), whereas water activity (aw) did not differ significantly (p = 0.607) (Table 4). EWP–XG showed the lowest numerical moisture content (5.02%), followed by SPI–XG (5.48%), EWP (5.97%), and SC–XG (6.01%). According to DMRT, EWP–XG did not differ significantly from SPI–XG, while EWP and SC–XG did not differ significantly from each other. SPI–XG also did not differ significantly from EWP or SC–XG. In contrast, all formulations showed statistically similar aw values. The lower moisture content observed in EWP–XG was consistent with its higher foam expansion and foam stability (Table 2). Improved foam structure can increase the effective surface area available for moisture removal during foam-mat drying, thereby facilitating heat and mass transfer [34,35]. However, this relationship was not uniform across the tested formulations, as SC–XG exhibited a moisture content comparable to EWP. This indicates that residual moisture differed among the tested foaming systems and could not be attributed to xanthan gum alone.

SC–XG showed the highest numerical aw value (0.41), while EWP–XG showed the lowest (0.28); however, these differences were not statistically significant. Therefore, the aw results should be interpreted as numerical variation rather than evidence of a treatment effect. All formulations exhibited relatively low aw values (0.28–0.41), which are favorable for the stability of dried powders [11]. Overall, the protein–polysaccharide foaming systems significantly influenced moisture content but did not significantly affect aw under the conditions evaluated. The differences in residual moisture may be associated with variations in foam characteristics and powder structure generated during drying, whereas the observed numerical differences in aw were not statistically distinguishable among formulations.

Table 5. Flow properties of foam-mat dried peanut worm powder with different foaming agents.

Foaming Agent	BD (g/cm^3)	TD (g/cm^3)	CI (%)	HR
EWP	0.53 ± 0.18^a	0.69 ± 0.12^b	23.80 ± 14.50^a	1.35 ± 0.27^a
EWP–XG	0.35 ± 0.09^a	0.39 ± 0.08^a	11.76 ± 5.12^a	1.14 ± 0.07^a
SPI–XG	0.41 ± 0.13^a	0.47 ± 0.10^a	14.43 ± 13.08^a	1.20 ± 0.21^a
SC–XG	0.56 ± 0.19^a	0.65 ± 0.06^b	15.85 ± 23.01^a	1.30 ± 0.52^a

Values are presented as means ± standard deviations (n = 5).

Values in the same column with the same superscript are not significantly different (p > 0.05).

BD, Bulk density; CI, Carr's index; EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; HR, Hausner ratio; SC–XG, Sodium caseinate and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; TD, Tapped density.

3.5. Hygroscopicity

Hygroscopicity differed significantly among the formulations (p < 0.001) (Table 4). EWP–XG showed the lowest hygroscopicity (10.62%), followed by SPI–XG (11.94%), while EWP (13.27%) and SC–XG (14.02%) showed higher values and did not differ significantly from each other. The lower hygroscopicity of EWP–XG indicated greater resistance to moisture absorption during storage. This result coincided with its lower moisture content, smaller particle size, and more uniform particle morphology compared with the other formulations. Previous studies have reported that powder hygroscopicity is influenced by particle characteristics, residual moisture, and formulation composition, all of which affect the accessibility of water to the powder surface [35,36]. In contrast, SC–XG exhibited the highest hygroscopicity together with the highest moisture content and a larger, more agglomerated particle structure observed by SEM. Differences in hygroscopicity among formulations may therefore be associated with differences in powder structure and formulation composition rather than moisture content alone. Hygroscopicity is an important quality attribute because excessive moisture absorption during storage may promote powder caking, reduce flowability, and shorten product shelf life [11,24]. Overall, the results suggest that the protein–polysaccharide foaming systems influenced the hygroscopic behavior of the powders through their effects on powder characteristics generated during foam-mat drying.

3.6. Flow Properties

The different protein–polysaccharide foaming systems significantly affected TD, whereas no significant differences were observed in BD, Carr's Index (CI), or HR among the formulations (Table 5). EWP–XG and SPI–XG exhibited significantly lower TD values than EWP and SC–XG. Although numerical differences were observed for BD, CI, and HR, these parameters did not differ significantly among treatments (p > 0.05). Numerically, EWP–XG exhibited the lowest BD, CI, and HR values, whereas EWP showed the highest CI and HR values. Lower CI and HR values generally indicate lower powder compressibility and cohesiveness; however, because the differences among formulations were not statistically significant, these values should be interpreted as numerical trends rather than evidence of a significant treatment effect on powder flowability. The lower numerical CI and HR values observed for EWP–XG coincided with its smaller particle size, more uniform morphology, and lower hygroscopicity. Powder flow behavior can be influenced by particle morphology, moisture-related properties, and particle packing [35,37]. The significant differences in TD indicate that the formulations differed in their packing behavior after tapping. Under the tapping conditions used in this study, EWP–XG and SPI–XG formed powder beds with lower tapped densities than EWP and SC–XG. Nevertheless, these differences in TD did not result in significant differences in CI or HR. Thus, the present results do not support a statistically significant difference in overall powder compressibility or cohesiveness among the formulations, despite the numerical variations observed in these parameters.

Table 6. Chemical properties of foam-mat dried peanut worm powder with different foaming agents.

Foaming Agent	Glutamic Acid (mg/100g)	Protein (%)	pH
EWP	2583.06 ± 70.29^a	3.27 ± 0.16^a	7.62 ± 0.05^d
EWP–XG	3184.25 ± 60.80^c	3.47 ± 0.09^b	7.44 ± 0.03^c
SPI–XG	2971.48 ± 55.37^b	3.76 ± 0.25^c	6.91 ± 0.08^b
SC–XG	3255.76 ± 91.08^c	4.18 ± 0.33^d	6.67 ± 0.07^a

Values are presented as means ± standard deviations (n = 5).

Values in the same column with the same superscript are not significantly different (p > 0.05).

EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; SC–XG, Sodium caseinate and xanthan gum.

Table 7. Glutamic acid content of blank formulations and corresponding foam-mat dried peanut worm powders.

Foaming Agent	Blank formulation (mg/100 g)	Peanut worm powder (mg/100 g)
EWP	247.62 ± 31.27^a	2583.06 ± 70.29^a
EWP–XG	417.19 ± 29.36^b	3184.25 ± 60.80^c
SPI–XG	538.38 ± 53.10^c	2971.48 ± 55.37^b
SC–XG	608.25 ± 55.19^d	3255.76 ± 91.08^c

Values are presented as mean ± standard deviation (n = 5).

Values in the same column with the same superscript are not significantly different (p > 0.05).

EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; SC–XG, Sodium caseinate and xanthan gum.

3.7. Chemical Properties

Glutamic acid content differed significantly among formulations (Table 6). SC–XG showed the highest numerical concentration, but it did not differ significantly from EWP–XG. Both formulations showed higher glutamic acid contents than SPI–XG and EWP. To assess whether the formulation ingredients themselves contributed measurable glutamic acid, blank formulations were prepared using identical formulation ingredients, with peanut worm extract replaced by distilled water. As shown in Table 7, all blank formulations contained measurable glutamic acid (247.62–608.25 mg/100 g), showing that measurable glutamic acid was present in the blank formulations themselves. However, because replacing peanut worm extract with distilled water altered the total solids composition and powder recovery of the blank formulations, direct quantitative comparison with the corresponding peanut worm powders cannot be used to estimate the percentage contribution of the formulation ingredients. Therefore, the blank data are interpreted only as evidence that the formulation ingredients themselves contained measurable glutamic acid, rather than as a quantitative estimate of their contribution to the final powder.

The higher glutamic acid concentrations observed in SC–XG and EWP–XG may reflect differences in formulation composition together with the contribution of peanut worm solids. Protein–polysaccharide systems have previously been reported to improve foam stability and modify the physicochemical properties of foam-mat dried products by stabilizing the foam structure during drying [18,26]. However, because molecular interactions were not directly characterized in the present study, this mechanism should be regarded as a plausible explanation

Table 8. Color profile of foam-mat dried peanut worm powder with different foaming agents.

Foaming Agent	*L	*a	*b	WI
EWP	85.27 ± 0.27^{c}	1.61 ± 0.08^{b}	7.36 ± 0.74^{b}	83.44 ± 0.39^{c}
EWP–XG	89.03 ± 0.83^{d}	1.33 ± 0.13^{a}	4.88 ± 0.82^{a}	87.88 ± 0.61^{d}
SPI–XG	81.36 ± 0.61^{a}	2.02 ± 0.15^{c}	9.84 ± 0.21^{d}	78.83 ± 0.60^{a}
SC–XG	83.72 ± 0.28^{b}	1.94 ± 0.04^{c}	8.19 ± 0.37^{c}	81.67 ± 0.30^{b}

Values are presented as means ± standard deviations (n = 5).

Values in the same column with the same superscript are not significantly different (p > 0.05).

EWP, Egg white powder; EWP–XG, Egg white powder and xanthan gum; SPI–XG, Soy protein isolate and xanthan gum; SC–XG, Sodium caseinate and xanthan gum.

supported by previous studies rather than direct experimental evidence. Protein content was highest in SC–XG and lowest in EWP. Interestingly, SPI–XG contained more protein than EWP–XG but exhibited a lower glutamic acid concentration, indicating that total protein content alone did not parallel the measured glutamic acid concentration. Because the amino acid profiles of the commercial protein ingredients were not determined and the blank design did not permit quantitative ingredient attribution, the specific contribution of each protein ingredient to the final glutamic acid content cannot be resolved from the present data. Although pH differed significantly among formulations, the differences were relatively small. Because sensory evaluation was not conducted in the present study, no direct conclusions can be drawn regarding the influence of these pH differences on perceived umami intensity.

3.8. Color Profile

Color parameters differed significantly among the formulations (p < 0.001) (Table 8). The EWP–XG formulation exhibited the highest L value (89.03) and whiteness index (WI, 87.88), together with the lowest a (1.33) and b* (4.88) values, indicating a brighter appearance with less pronounced red and yellow coloration. In contrast, SPI–XG exhibited the lowest L* (81.36) and WI (78.83) and the highest b* value (9.84). SPI–XG also showed the highest numerical a* value (2.02), although it did not differ significantly from SC–XG (1.94). The observed differences in color may be associated with differences in formulation composition and thermal reactions occurring during foam-mat drying. Previous studies have reported that non-enzymatic browning, particularly Maillard reactions between amino compounds and reducing sugars, contributes to color development in protein-containing dried foods [38]. In addition, moisture-related conditions have been reported to influence browning reactions during thermal processing [39]. In the present study, the EWP–XG formulation also exhibited the lowest moisture content, which coincided with its brighter appearance. However, the extent of the Maillard reaction was not directly evaluated; therefore, these explanations should be regarded as plausible mechanisms supported by previous studies rather than direct experimental evidence. Differences in protein source may also contribute to variations in color development because proteins differ in their amino acid composition and thermal behavior during drying [40,41]. Overall, the EWP–XG formulation produced the brightest powder and the highest whiteness index among all treatments.

3.9. YIELD

Yield differed significantly among the formulations, with the highest value observed in SC–XG (76.01%) and the lowest in EWP (64.37%) (Fig. 3). EWP–XG, SPI–XG, and SC–XG produced higher numerical yields than EWP. These results were consistent with the higher foam

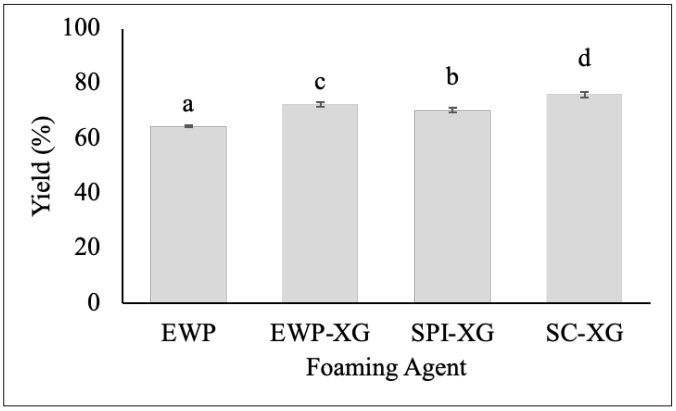

Figure 3. Yield of foam-mat dried peanut worm powder with different foaming agents. Egg white powder (EWP), a mixture of EWP–xanthan gum (EWP–XG), soy protein isolate-XG (SPI–XG), and sodium caseinate–XG (SC–XG). Values are means ± SD (n = 5). Different letters indicate significant differences among formulations (DMRT, p < 0.05).

expansion and foam stability observed for EWP–XG, SPI–XG, and SC–XG compared with EWP, suggesting that the foaming system influenced powder recovery during foam-mat drying. Powder yield in foam-mat drying can be influenced by formulation composition and foaming conditions, which affect the structural characteristics of the foam and the resulting dried matrix [42]. Although SC–XG exhibited the highest yield, it did not consistently exhibit the most favorable physicochemical properties. Compared with EWP–XG, the SC–XG formulation produced larger particles and showed lower rehydration performance. These findings indicate that a higher powder yield does not necessarily correspond to superior powder quality. Therefore, selection of an appropriate protein–polysaccharide foaming system should consider both process efficiency and the functional characteristics of the resulting powder.

4. CONCLUSION

This study evaluated the effects of different protein–polysaccharide foaming systems on the physicochemical and functional properties of foam-mat dried peanut worm (*Siphonosoma australe*) powder. Among the evaluated formulations, EWP–XG exhibited favorable characteristics, including higher foam expansion and stability, smaller particle size, superior rehydration characteristics, lower moisture content and hygroscopicity, and a brighter color. In contrast, SC–XG produced the highest powder yield and the numerically highest glutamic acid content, although its glutamic acid content did not differ significantly from that of EWP–XG, while showing comparatively lower rehydration performance. Blank formulation analysis showed that the formulation ingredients themselves contained measurable glutamic acid; however, their relative quantitative contribution to the final powder could not be determined from the present blank design. Overall, the results demonstrate that different protein–polysaccharide foaming systems produced distinct physicochemical and functional characteristics in the resulting powders. A limitation of the present study is that a full factorial experimental design was not employed to separately evaluate the individual and combined effects of the protein sources and xanthan gum. In addition, molecular interactions between proteins and xanthan gum were not directly characterized. Therefore, future studies incorporating individual protein controls, xanthan gum-only formulations, a full factorial experimental design, and direct characterization of protein–polysaccharide interactions are recommended to provide a more comprehensive understanding of the mechanisms underlying foam-mat drying systems.

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6. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

7. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

8. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to the conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be authors as per the International Committee of Medical Journal Editors (ICMJE) requirements and guidelines.

9. DATA AVAILABILITY

All the data are available with the authors and shall be provided upon request.

10. PUBLISHER'S NOTE

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11. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

During the preparation and revision of this manuscript, the authors used ChatGPT (OpenAI) for language refinement, grammatical editing, and improving the clarity and organization of selected passages. The AI tool was not used to generate experimental data, perform laboratory analyses, conduct statistical analyses, generate or manipulate images, or fabricate scientific results. All scientific content, data interpretation, references, and final wording were critically reviewed and verified by the authors, who take full responsibility for the final manuscript.

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