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APPLICATION OF MATERIAL FLOW ANALYSIS (MFA) ON BIOVALORIZATION SYSTEM OF SOY SAUCE AND TOFU SOLID WASTE INTO SEASONING SAUCE PRODUCTS

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Abstract

The massive volume of agroindustrial solid waste from soy sauce (59.7%) and tofu (35.5%) production has the potential to pollute the environment if it ends up in water bodies. However, the high nutrient content opens up opportunities for biovalorization into value-added products. Soy sauce solid waste has a protein content of 16.31%, and tofu solid waste has a protein content of 4.78%. This study aims to produce a plant-based sauce from soy sauce and tofu residues by adding banana peel pectin as a thickener, while simultaneously calculating the waste reduction rate using Material Flow Analysis (MFA) with STAN 2.7.101 software. The method used was solid-state fermentation (SSF) for 72 hours using Aspergillus oryzae and Aspergillus sojae. The sauce characteristics were evaluated through pH, protein content, and organoleptic testing using a scoring method (1–5) to determine the best treatment. From the MFA mapping, it was proven that the biovalorization process of soy sauce residue-based sauce was able to reduce solid waste by up to 55.14%, which is more efficient compared to tofu residue, which only reduced waste by 44.51%.

Keywords: *Biovalorization*, *Material Flow Analysis, Waste Reduction, Aspergillus, Solid Waste.*

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1. Introduction

The production processes for soy sauce and tofu generate solid waste as a byproduct. Soy sauce production generates solid waste equivalent to 59.7% of the soybeans used as raw material. Meanwhile, tofu production generates solid waste equivalent to 35.5% of the tofu produced (Sjafruddin et al. 2022). Untreated solid waste often ends up in rivers. Soy sauce waste contains high levels of organic matter with a pungent odor (Hendrasarie et al. 2022). The high organic content in the waste leads to increased BOD and COD when mixed into water bodies (Hendrasarie 2026). In addition to soy sauce waste, tofu waste has high levels of BOD, COD, TSS, ammonia, nitrate, and nitrite (Hendrasarie et al. 2022).

Furthermore, both types of waste contain high levels of nutrients. Soy sauce solid waste contains 16.31% protein, 6.22% carbohydrates, and 18.05% fat (Hendrasarie et al., 2025). Tofu solid waste contains 4.78% protein, 23.42% carbohydrates, and 0.41% fat. This high protein content opens up the potential for isolated essential amino acids (Vong et al. 2016), which play a crucial role in the body and in children's growth and development (Saras 2023). Solid-state fermentation (SSF) using the molds *Aspergillus oryzae* and *Aspergillus sojae* can break down proteins into glutamic acid (L-glutamate), a key component of the umami flavor (Vong et al. 2016).

The umami flavor potential resulting from this fermentation can be developed into a flavor-enhancing sauce. In its production, this seasoning sauce uses pectin from banana peels as a gelling agent. This processing is carried out to reduce waste. Waste reduction calculations were performed using the Material Flow Analysis (MFA) approach by mapping the mass balance and material flow (Brunner & Rechberger 2017) using the STAN 2.7.101 application.

Despite growing interest in valorizing soy sauce and tofu residues, previous work has largely focused on either wastewater treatment or single-substrate fermentation, and few studies have quantified the actual mass of solid residue diverted from disposal. A direct, side-by-side comparison of soy sauce versus tofu solid waste under identical fermentation conditions remains scarce, leaving it unclear which residue offers greater valorization potential. The present study addresses this gap by (i) comparing both residues as fermentation substrates under identical conditions; (ii) contrasting two koji molds—*A. oryzae* (predominantly amylolytic) and *A. sojae* (predominantly proteolytic)—to relate enzymatic profile to umami development; (iii) incorporating banana-peel pectin as a low-cost natural thickener to convert the hydrolysate into a usable sauce; and (iv) applying Material Flow Analysis to quantify, rather than merely assert, the reduction of solid residue achieved by the process.

2. Method

2.1 Production of Flavoring Sauce

Solid waste is prepared by sterilizing it through boiling at 100°C for 15 minutes. Before fermentation, the pH and moisture content are adjusted. The ideal pH for A. oryzae is 5.0–6.0, and for A. sojae, it is 4.5–5.5. Fermentation is then carried out using *Aspergillus* mold at 35°C for 72 hours. The fermentation product is subsequently sterilized at 100°C for 15 minutes. The mixture is then filtered, and the separated filtrate is seasoned with the following ingredients: leek (5%), shallots (5%), garlic (5%), sugar (2.5%), and salt (5%). The seasoning sauce is thickened with 1% w/v banana peel pectin.

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2.2 *Preparation of Banana Peel Pectin Gelling Agent*

The banana peel pectin gelling agent was prepared via acid extraction using 5% citric acid at 85°C for 90 minutes (Musafara et al. 2024). The extraction filtrate was then treated with 96% ethanol for precipitation over 24 hours. The precipitation residue was then dried at 50°C until constant weight. The dried pectin was subsequently ground and sieved through an 80-mesh sieve.

2.3 *Variable and Product Analysis*

The variables in this study were the types of solid waste used—namely soy sauce and tofu waste—and the fermentation molds employed, specifically *Aspergillus oryzae* and *Aspergillus sojae*. During the fermentation process, pH measurements were taken every 12 hours to monitor changes in pH (Kabir et al. 2025). The resulting product was then tested for protein content using the Kjeldahl method. Sensory evaluation was performed by 35 semi-trained panelists (16 male, 19 female, age range 18 - 23 years old) using the 1-5 scoring scale in Table 1 for color, aroma, taste, and texture, based on SNI 01-2346-2006. Each sample was labeled with a three-digit random code and presented in randomized order; panelists cleansed their palate with mineral water between samples. Participation was voluntary, and informed consent was obtained from all panelists prior to evaluation. Sensory characteristics (taste, aroma, color, and texture) obtained from the study will then be analyzed using the Friedman test (n = 35), followed by pairwise Wilcoxon signed-rank tests with Bonferroni correction (adjusted alpha = 0.0083) for attributes that were significant.

Table 1. *Scoring Scale*

Score	Scoring Scale			
	Taste	Aroma	Color	Texture
5	Strong umami flavor	Very fragrant, typical of seasoning sauces	Brown	Very thick
4	Umami	Fragrant, typical of seasoning sauce.	Yellowish brown	Thick
3	Slight umami flavor	Slightly fragrant	Yellow	Slightly thick
2	Very slight umami flavor	Slightly rancid	Cream	Slightly watery
1	No umami flavor	Rancid	Pale white	Watery

2.4 *Material Flow Analysis (MFA)*

Material Flow Analysis (MFA) is a method used to map, measure, and manage material flows and inventories within a production process system, from raw material inputs to product outputs, waste, and emissions (Brunner & Rechberger 2017). Before

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conducting the analysis, a system definition is first established. Measurements are taken for each process, the materials input, and the waste generated. The measurement results are calculated using STAN 2.7.101 software. System boundaries of material flow analysis are shown in Figure 1. The system boundaries encompass the pre-treatment of agro-industrial solid waste and pectin extraction as inputs, flowing through solid-state fermentation to the final formulation. The outputs are categorized into the value-added product (vegan sauce), solid residues, and inherent mass losses (e.g., CO_2 emissions and water evaporation). To evaluate the biovalorization efficiency in diverting waste from landfills, the waste reduction percentage is calculated using the following formula:

$$\text{Waste Reduction (\%)} = \left(\frac{Total\ Input - Total\ Residue}{Total\ Input}\right) \times 100\%$$

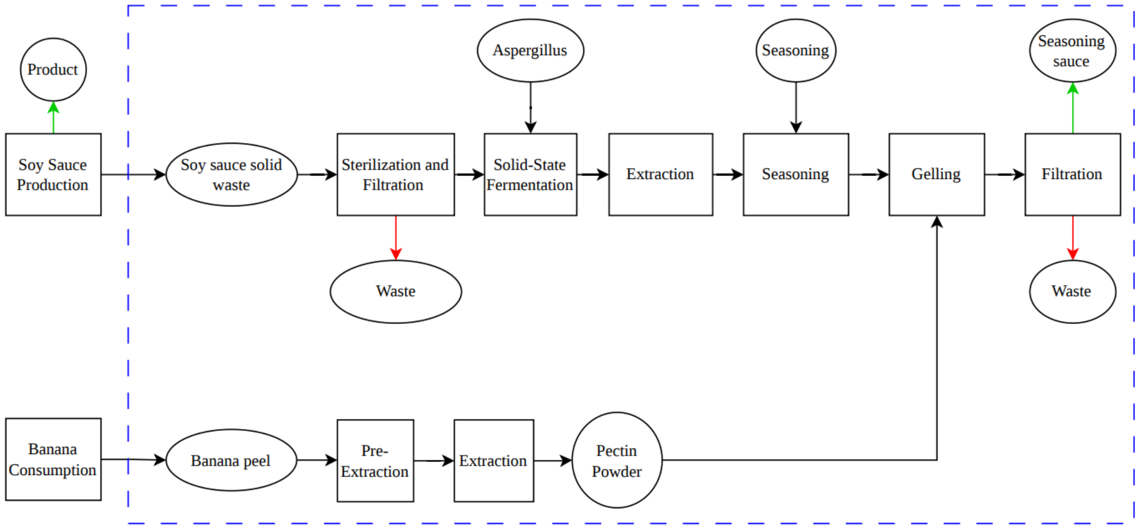

Figure 1. System Definitions of MFA

2.5 Statistical Analysis

Because each treatment was produced as a single, unreplicated batch, protein content is reported descriptively as the mean ± half the range of duplicate determinations per sample (the ± value denotes the spread between the two readings, not a standard deviation), and no inferential test was applied to this parameter with respect to the fermentation treatments. For pH, a single measurement was recorded for each treatment at every sampling time (0, 12, 24, 36, 48, 60, and 72 h), yielding one time-series trajectory per fermentation unit rather than replicate observations at any given time point; pH is therefore presented as the measured value at each sampling time (Figure 2) and described qualitatively in terms of its temporal trend, with no error bars or inferential comparisons among treatments. For the sensory evaluation, each of the 35 panelists scored all four samples; because the scores are ordinal and repeated within panelists, treatment differences for each attribute were assessed using the non-parametric Friedman test, with pairwise comparisons by the Wilcoxon signed-rank test with manual Bonferroni correction (adjusted $\alpha = 0.0083$, i.e., 0.05/6 comparisons), at an overall significance level of $\alpha = 0.05$. Sensory results are expressed as median (interquartile range) per attribute per sample. All sensory analyses were performed using SPSS v32.

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Research Limitation

The experiment followed a 2 × 2 factorial design (residue type: soy-sauce vs. tofu; mold: *A. oryzae* vs. *A. sojae)*, yielding four treatment combinations (KAO, KAS, TAO, TAS). Each treatment was prepared from one production batch using 248-286 g solid waste. The study did not include an untreated (unfermented) control and did not include independent replicate batches; pH was therefore monitored over time on a single fermentation unit per treatment, and protein content was determined in duplicate analytical measurements per sample. These constraints are stated explicitly in the Limitations section.

3. Result and Discussion

3.1 Solid-State Fermentation (SSF)

Fermentation was carried out using two types of mold, namely *A. oryzae* and *A. sojae.* Fermentation was conducted at 35°C for 72 hours with a moisture content of 40–60%. The moisture content was adjusted using a food dehydrator set at 50°C. The fermentation process in *Aspergillus* molds can affect the pH value of the material due to mold growth (Musafara et al. 2024). The initial pH of soy sauce solid waste is 5.2, and the initial pH of tofu solid waste is 5. Both pH values meet the ideal conditions for fermentation, where *A. oryzae* has an ideal pH range of 5.0–6.0 (Seidler et al. 2024), while *A. sojae* has an ideal pH range of 4.5–5.5 (Ito et al. 2021).

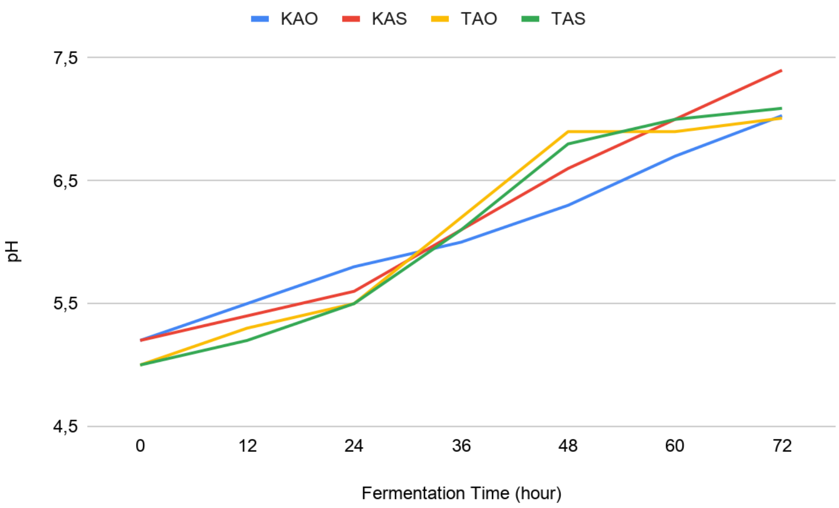


Figure 2. Changes in pH During Fermentation

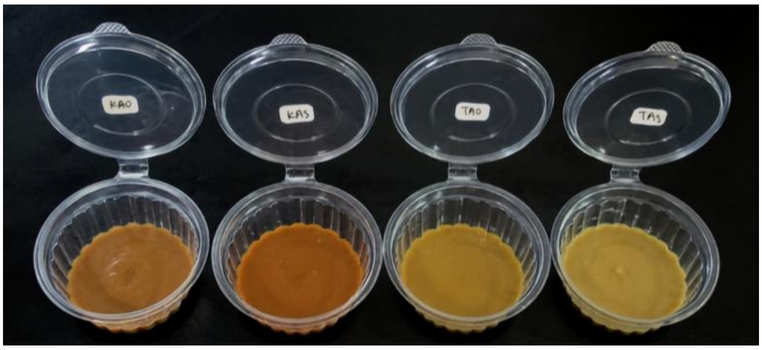
KAO: Soy sauce waste fermented by *A. oryzae*; KAS: Soy sauce waste fermented by *A. sojae*; TAO: Tofu waste fermented by *A. oryzae*; TAS: Tofu waste fermented by *A. sojae*.

The dynamics of pH changes during the 72-hour fermentation period are illustrated in Figure 2. This reflects a significant increase in pH due to fungal metabolic and respiratory activity during the 72-hour fermentation period in the soy sauce residue (KAO, KAS) and tofu residue (TAO, TAS) groups. Starting from ideal initial pH conditions (5.0–5.2), all samples reached neutral conditions by the end of the incubation period, with the highest increase observed in the KAS treatment (7.4), while KAO, TAO, and TAS remained stable in the range of 7.0–7.1. The rise in pH reflects a change in the chemical condition of the substrate during fermentation—plausibly due to the proteolytic release of basic nitrogenous compounds—which indicates active fungal growth. This observed upward trend toward neutrality aligns with established metabolic patterns reported in previous Aspergillus solid-state fermentations (Vong and Liu 2016; Li et al. 2023), confirming that the molds successfully altered the substrate medium.

3.2 Sensory Evaluation: Scoring Method

Organoleptic evaluation using a scoring method (1-5 scale) revealed that the vegan sauce derived from soy sauce waste fermented with Aspergillus sojae (KAS) was the overall best treatment. The KAS treatment achieved the highest score for the taste attribute (4.3) due to the robust protease enzyme activity of A. sojae, which hydrolyzes proteins into glutamate amino acids, thereby generating a dominant umami flavor. Conversely, the A. oryzae mold was slightly superior in the aroma attribute due to the secretion of ester compounds that produce a distinctive fragrant aroma, while the optimal brown color was consistently dominated by all samples within the soy sauce waste group. Each sensory attribute was tested separately for differences among the four samples using the Friedman test ($n = 35$), followed by pairwise Wilcoxon signed-rank tests with Bonferroni correction (adjusted alpha = 0.0083) for attributes that were significant. Taste ($x2 = 26.46$, $p < 0.001$), color ($x2 = 65.664$, $p < 0.001$), and texture ($x2 = 39.427$, $p <0.001$) significantly among samples, where aroma did not ($x2 = 5.795$, $p = 0.158$). For taste KAS scored significantly higher than TAO ($Z = -3.774$, $p < 0.001$, $r = 0.479$) and TAS ($Z = -2.834$, $p < 0.001$, $r = 0.36$), and KAO scored higher than TAO ($Z = -3.636$, $p < 0.001$, $r = 0.462$). Table 2 shows that the fermentation results using A. sojae yielded higher values for both types of waste compared to A. oryzae. During the fermentation process, A. sojae exhibits high protease activity, resulting in a strong umami flavor (Vong et al., 2016). Meanwhile, in A. oryzae, amylolytic activity is more dominant, producing a sweeter taste and a strong volatile aroma (Vong et al. 2016). Aspergillus fermentation breaks down proteins into glutamic acid (L-glutamate), which forms the umami flavor (Vong et al. 2016). This difference in protein values results in a higher scoring value for soy sauce residue due to the formation of more glutamic acid.

For color, both soy sauce samples (KAO, KAS) scored higher than both tofu samples (TAO, TAS) (all $p < 0.0083$). Figure 3 shows soy sauce waste produces more brown samples both in KAO and KAS. While tofu waste produces samples in a lighter color. Lighter-colored made tofu samples have a lower score than soy sauce.



(a) (b) (c) (d)

Figure 3. (a) Soy sauce—*A. oryzae*; (b) Soy sauce—*A. sojae;* (c) Tofu—A. *oryzae;* (d) Tofu—*A. sojae.*

For texture, TAO was not significantly different from KAO and KAS ($p > 0.0083$). Significance groupings are shown by superscript letters in Table 2. The optimal texture of the sauce was achieved through the addition of banana peel pectin as a natural thickener. The extraction process utilized an initial wet mass of 107.6 g of banana peels, which was reduced to a dry mass of 21.7 g. This process yielded 2.5 g of pectin, representing an extraction yield of 11.5%. The application of this 1% pectin successfully produced a desirable sauce consistency with a viscosity of 474 cP. Viscosity was measured using a Brookfield viscometer, model RVT, spindle no. 3, 50 rpm, at 25°C.

Table 2. Sensory Evaluation Result

Sample	Taste	Aroma	Color	Texture
KAO	4 (4-5) a	4 (3-4)	5 (4-5) a	3 (2-4) b
KAS	4 (4-5) ab	3 (3-4)	4 (4-5) a	4 (3-4) c
TAO	3 (2-4) bc	3 (3-4)	2 (1-3) b	3 (2-4) a
TAS	4 (3-4) c	3 (3-4)	3 (3-4) c	5 (4-5) bc

Values are the median (Q1-Q3) of 35 panelists. Within each column, samples sharing a superscript letter are not significantly different; samples with no common letter differ significantly (Friedman test followed by pairwise Wilcoxon signed-rank tests, Bonferroni-adjusted alpha = 0.0083) Aroma showed no significant difference (Friedman $x^2 = 5.795$, $p = 0.112$). Friedman results - taste: $x^2 = 26.46$, $p < 0.001$; color: $x^2 = 65.664$, $p < 0.001$; texture: $x^2 = 39.427$ $p < 0.001$

Table 3. Protein Content in Seasoning Sauce

Sample Name	Protein Content (%)
Soy sauce waste fermented by *A. oryzae*	1.73 ± 0.02%
Soy sauce waste fermented by *A. sojae*	2.46 ± 0.04 %
Tofu waste fermented by *A. oryzae*	0.90 ± 0.03 %
Tofu waste fermented by *A. sojae*	1.47 ± 0.03 %

Protein contents are presented as the mean ± half the range of duplicate determinations: KAO 1.73 ± 0.02%, KAS 2.46 ± 0.04%, TAO 0.90 ± 0.03%, and TAS 1.47 ± 0.03% (Table 3). The highest protein content was obtained in the soy-sauce residue fermented with A. sojae (KAS), consistent with the strong proteolytic activity of this species (Li et al. 2023). As noted in the Methods, these values are reported descriptively and were not tested statistically. The results of the protein content analysis of the plant-based sauce products in Table 3 show a direct correlation with the formation of the umami sensory profile. During the solid-state fermentation (SSF) process, protease enzymes secreted by Aspergillus fungi hydrolyze the complex protein bonds in the pomace into free amino acids, primarily L-glutamate (Li et al. 2023). High protease activity, particularly in the treatment using A. sojae mold, which has high protease activity, resulted in higher final protein content and better umami scores compared to the A. oryzae treatment.

3.3 Material Flow Analysis (MFA)

The production of seasoning sauce in a single batch requires 248–250 grams of soy sauce solid waste and 269–286 grams of tofu solid waste, with each batch producing 249–255 grams of flavor enhancer sauce. A single batch of flavor enhancer sauce production requires 2.5 grams of banana peel pectin. The selection of raw materials for the seasoning sauce was based on the high volume of solid waste generated from soy sauce and tofu production, as well as banana consumption (Hendrasarie et al. 2026). Organic waste discharged into water bodies can increase BOD, COD, and TSS levels (Hendrasarie et al. 2021). The MFA is intended to illustrate the production flow of the sauce and the resulting waste.

The material flow model based on STAN 2.7.101 software (Figure 4 and Figure 5) systematically maps the biovalorization route of solid waste. Mass flow is traced from the raw material washing stage through banana peel pectin extraction to the mold fermentation phase. Subsequently, the filtrate flow enters the final filtration stage, spice mixing, and thickening process to produce a plant-based sauce ready for testing. Every input and output is calculated with precision, including waste generated from the manufacturing process (Hendrasarie et al. 2023).

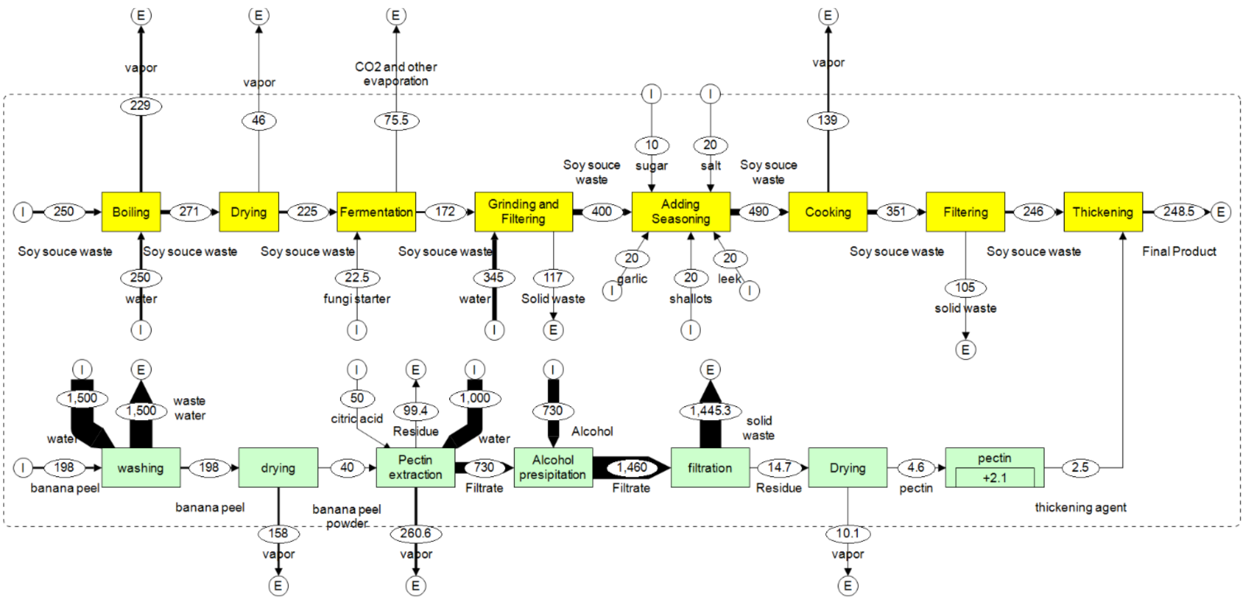


Figure 4. Material Flow Analysis of Fermented Soy Sauce Residue by A. sojae
Note: The dashed lines indicate the system boundaries; all figures are given in grams/batch.

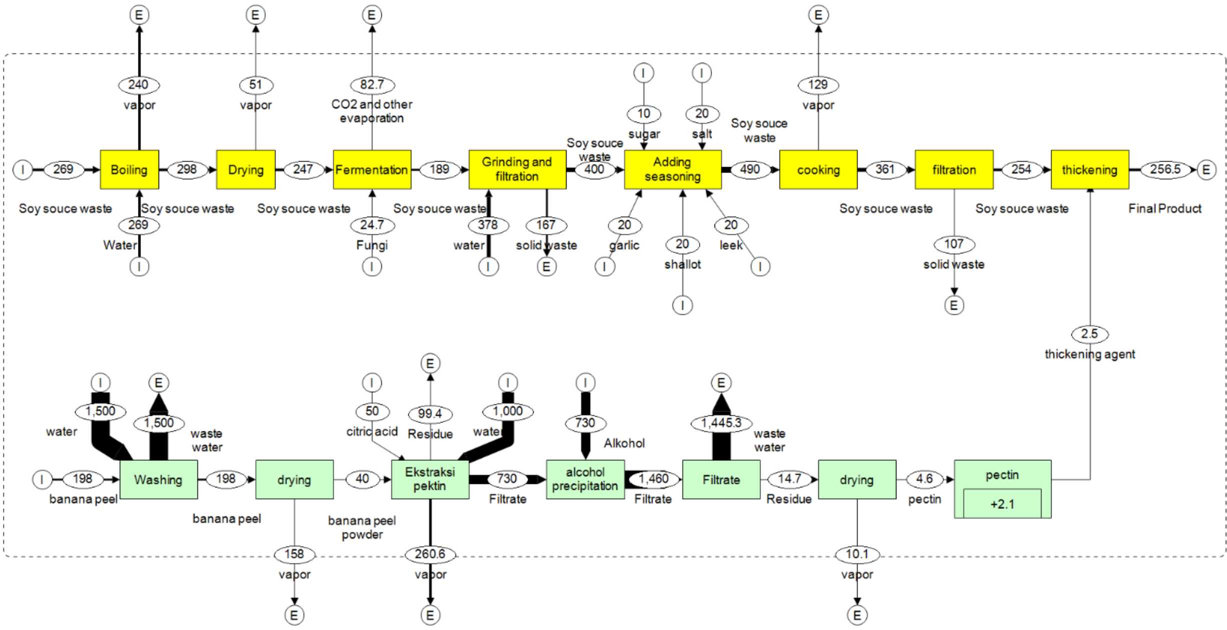


Figure 5. Material Flow Analysis of Fermented Tofu Residue by *A. sojae*

Note: The dashed lines indicate the system boundaries; all figures are given in grams/batch.

Table 4. Reduction of Solid Waste in the Production of Seasoning Sauce

Sample Name	Solid Waste Reduction (%)
Soy sauce waste fermented by *A. oryzae*	55.14%
Soy sauce waste fermented by *A. sojae*	53.03%
Tofu waste fermented by *A. oryzae*	42.18%
Tofu waste fermented by *A. sojae*	44.51%

During the vegan sauce production process, several mass losses occurred due to evaporation during boiling, CO_2 release during fermentation, solid residue separation during filtration, and moisture reduction during drying. The results of the MFA analysis indicate that tofu-based sauces require more tofu pulp and generate more solid waste compared to soy sauce pulp. The solid-residue reduction achieved here (53–55% for soy-sauce residue) is comparable to values reported for other agro-industrial valorization routes, such as a 70.65% reduction in mixed organic and food waste bioconversion evaluated via MFA (Zahra et al. 2024). In contrast to studies that report valorization only qualitatively, the present MFA quantifies the diverted mass, strengthening the evidence base for residue-to-product conversion. The dominance of *A. sojae* in umami development is consistent with its high proteolytic activity reported by Li et al. (2023), while the larger residual mass from tofu waste aligns with its higher moisture content (70.06% vs. 58.67%), in agreement with Vong and Liu (2016).

This study has several limitations. First, it was conducted at laboratory scale with a single, unreplicated batch per treatment and no untreated control, which limits statistical inference and generalization to production scale. Second, free glutamate—the molecular basis of the umami claim—was not quantified directly and was only inferred from total protein and sensory scores. Third, product safety, microbiological stability, and shelf life were not assessed. Fourth, energy and reagent inputs (heating, drying, citric acid, ethanol) were not included in the mass balance, so the MFA captures solid-residue reduction only and not the full environmental footprint. Fifth, the number of treatments (n = 4) was limited. These points define clear directions for future work.

4. Conclusion

Considering both the highest protein content and umami score, soy-sauce residue fermented with *A. sojae* (KAS) represents the most favorable combination, although the single highest waste-reduction value (55.14%) was recorded for KAO. The high protease enzyme activity in this mold significantly results in the highest protein content and the best umami taste organoleptic score compared to other treatments. From an environmental management perspective, Material Flow Analysis (MFA) mapping confirms that the biovalorization of soy sauce residue achieves a high level of waste reduction efficiency, reaching 55.14% more effectiveness than soybean tofu residue, which only reduces waste by 44.51%. The utilization of this combination of agro-industrial waste and banana peel pectin has proven effective in creating value-added substitute products.

AI Writing Statement

The authors confirm that no generative AI or AI-assisted tools were used in the writing, translation, analysis, or preparation of this manuscript.

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