

ECO-FRIENDLY BIOCONVERSION OF FRUIT WASTE INTO SINGLE-CELL PROTEIN BY *ASPERGILLUS NIGER*

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Abstract The increasing demand for sustainable and affordable protein sources has intensified interest in single-cell protein (SCP) production using agro-industrial wastes. This study evaluated the potential of watermelon rind (WR), mango seed kernel (MSK), and their combined formulation (50:50) as substrates for SCP production using *Aspergillus niger* under solid-state fermentation conditions. The substrates were collected locally, pretreated, and fermented for seven days, followed by optimization of key growth parameters including pH, temperature, and moisture content. Fungal biomass yield and crude protein content were determined using standard analytical methods. Among the tested substrates, the combined MSK: WR formulation produced the highest biomass yield (4.28 ± 0.21 g per 10 g substrate), significantly exceeding yields obtained from MSK (3.62 ± 0.18 g) and WR (2.85 ± 0.12 g). Optimization experiments revealed that maximum SCP production occurred at pH 5.0 (4.31 ± 0.19 g), a temperature of 25 °C (4.34 ± 0.20 g), and 70% moisture content (4.39 ± 0.22 g). Crude protein analysis showed substantial protein enrichment following fermentation, with the highest protein content observed in SCP produced from the combined substrate ($51.8 \pm 2.1\%$), followed by MSK ($44.9 \pm 1.7\%$) and WR ($38.6 \pm 1.4\%$). Statistical analysis confirmed significant differences ($p < 0.05$) among substrates and fermentation conditions. The findings demonstrate that watermelon rind and mango seed kernel, particularly when used in combination, are effective low-cost substrates for SCP production. This approach offers a sustainable strategy for converting fruit wastes into protein-rich biomass, contributing to alternative protein development and environmental waste reduction.

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Introduction

Introduction

Protein is a vital macronutrient that is needed to build up and repair tissues, produce enzymes, and maintain immunity as well as overall metabolism. Protein deficiency is an issue of great significance, but it is also a prevalent nutritional problem, especially in underdeveloped nations where the high-quality protein sources are not easily accessible due to economic, environmental, and agricultural factors. The growth of population, urbanization, climate change, and the increase in food demand have put strain on traditional protein sources, particularly those that are of animal origin, which consume vast quantities of land, water, and feed resources (Nirmal et al., 2025). Proteins of animal origin are

nutritionally complete, but their production is connected to very high environmental costs like greenhouse gas emissions, deforestation, water use, and competition with human food crops. In livestock farming, there is also a huge contribution to the use of antimicrobials and environmental pollution as well. Plant-based proteins, in turn, are greener but do not always include all essential amino acids and may have antinutritional effects affecting protein bioavailability (Malila et al., 2024).

Single Cell Protein (SCP) is the dried microbial biomass or protein derived by growing microorganisms, e.g., bacteria, yeasts, fungi, algae, and by using different substrates. The features of SCP are high protein content (usually 40-80%), a high rate of biomass growth, and the possibility to

utilize low-cost raw materials, such as agricultural and industrial wastes ([Nasseri et al., 2011](#)). The idea of SCP was brought into the limelight as a possible way of helping to overcome protein deficiencies in the world because of its many benefits over traditional protein sources. The microbes used in producing SCP have short generation time, high growth rate, and can be cultured at any time of the year regardless of climatic conditions. Furthermore, SCP manufacturing does not involve the use of arable land and can be done with renewable and high-availability substrates, making it especially appropriate in resource-constrained environments ([Suman et al., 2015](#)). SCP has been tested with a large variety of microorganisms, such as bacteria (*Methylophilus*, *Bacillus* spp.), yeasts (*Saccharomyces cerevisiae*, *Candida utilis*), filamentous fungi (*Aspergillus*, *Fusarium*), and microalgae (*Chlorella*, *Spirulina*). Of these, filamentous fungi have received significant interest because they can grow on a wide range of complex substrates, withstand changing environmental conditions, and generate biomass with desirable textural and nutritional characteristics ([Najafpour, 2007](#)).

A. niger is among the most widely examined fungal strains in the production of SCP. Categorically, it is safe (GRAS) in industrial applications and is commonly used in making enzymes, organic acids, and fermented food products. *A. niger* has a robust enzymatic system that can break down complex carbohydrates like cellulose, hemicellulose, and pectin, making it an effective user of lignocellulosic and fruit-based wastes as a source of growth ([Reihani & Khosravi-Darani, 2019](#)). A number of studies have shown that *A. niger* is effective in transforming agro-industrial wastes into protein-based biomass. It has a fast growth rate, produces high amounts of protein, and is flexible, making it a good choice to produce SCP with low-cost substrates ([Ekloh & Yafetto, 2024](#)). A significant international environmental issue is the production of post-agricultural industrial wastes. Harvesting, processing, transportation, and marketing of fruits and vegetables produce large amounts of waste. These wastes are commonly discarded in landfills or through open dumping, creating environmental pollution, greenhouse gas emissions, and causing health problems for the population ([Sadh et al., 2018](#)).

Fruit by-products such as watermelon rind and mango seed kernel are plentiful in tropical and subtropical areas, including Pakistan. The rind of watermelon makes up a large part of the mass of the fruit and is usually thrown away even though it contains abundant carbohydrates, fiber, as well as minerals. Another underutilized waste is mango seed kernel, which is a source of significant amounts of starch, lipids, and bioactive compounds that can be used to feed microbes ([Ekloh & Yafetto, 2024](#)).

Nevertheless, it is also observed that there is a research gap in the literature about the use of watermelon rind and mango seed kernel as a mixed substrate in producing SCP. Investigation of their joint potential can help to enhance the balance of substrates, improve the availability of nutrients, and improve the overall yield of protein.

Materials and methods

Collection of Raw Materials

Mango Seed Kernels (MSK) and watermelon rinds (WR) were collected in Peshawar, Khyber Pakhtunkhwa, Pakistan, in the local fruit markets and fruit juice vendors. Suitability of the substrate was ensured by means of picking only high-quality, undamaged, and mold-free samples. The gathered samples were put into sterile plastic bags and taken to the microbiology lab immediately in aseptic conditions ([Ahmed et al., 2024](#); [Thiviya et al., 2021](#)).

Inclusion and Exclusion Criteria

Only mango seeds and watermelon rinds that were free of visible spoilage were used in the study. The substrates used were clean and free of molds and deemed to be good to be fermented by the microbes. Moreover, only the parts of the fruit which could be easily cleaned, dried, and processed into a homogeneous powder were utilized. Any material of fruit which bore any indication of spoilage, fungousness, mechanical injury, or over-ripening was also excluded. Parts of fermented fruit, the outer green peel of watermelon, and parts of mango seeds that could not be processed safely or uniformly were also excluded. Moreover, any substrates that were contaminated with sand, dirt, or chemical remains could not be taken into consideration or used in the experiment.

Preparation and Pre-treatment of Substrates

Mango Seed Kernel (MSK)

The mango seeds were washed to get rid of any pulp. To remove the kernels, the hard seed coats were broken with a sterilized hammer. The kernels were cut into small pieces and sun-dried for 3-4 days and dried in an oven at 60°C overnight to remove moisture content ([Abdurrazag et al., 2025](#)). The dried kernels were ground to a fine powder with the help of a mechanical grinder, sieved through a 1mm mesh to obtain a uniform particle size, and kept in airtight containers at room temperature till further use.

Watermelon Rind (WR)

The white part of the watermelon rind, without the green peel, was rinsed in distilled water and cut into little cubes. The cut rind was dried in the oven at 60°C for 36 hours. The dried rind was then powdered finely and kept in airtight containers, just like MSK ([Thiviya et al., 2021](#)).

Substrate Formulation and Media Preparation

Three substrate formulations were made: 100% MSK, 100% WR, and a 50:50 mixture of MSK and WR (w/w). For each formulation, 10 grams of substrate were weighed into 250 mL Erlenmeyer flasks. Each flask was supplemented with 20 mL of a

nutrient solution containing ammonium sulfate ((NH₄)₂SO₄) at 1.0g/L, potassium dihydrogen phosphate (KH₂PO₄) at 1.0 g/L, magnesium sulfate heptahydrate (MgSO₄·7H₂O) at 0.5 g/L, and yeast extract at 0.5g/L (Asghar *et al.*, 2025). The moisture content was adjusted to 65–70%, and the pH was set between 5.5 and 6.0 using 1 N NaOH or HCl. Flasks were sterilized by autoclaving at 121°C for 15 minutes.

Inoculum Preparation

A. niger was cultured on potato dextrose agar (PDA) plates and incubated at 28 °C for 5–7 days to allow sporulation (Ahmed *et al.*, 2024; Abdurrazzaq *et al.*, 2025). Ten milliliters of sterile distilled water containing 0.01% Tween 80 were added to the culture plates, and spores were gently scraped and filtered through muslin cloth to remove mycelial fragments. The spore suspension was adjusted to 1×10^6 spores/mL using a hemocytometer.

Inoculation and Solid-State Fermentation (SSF)

Two milliliters of the prepared *A. niger* spore suspension were aseptically inoculated into each flask containing the prepared substrate. The flasks were incubated under static SSF conditions at room temperature for 7 days (Ahmed *et al.*, 2024; Thiviya *et al.*, 2021).

pH Optimization

Substrate pH was adjusted to 4.0, 5.0, 6.0, 7.0, and 8.0 using 1 N NaOH or HCl to assess fungal growth and protein synthesis under acidic, neutral, and slightly alkaline conditions.

Temperature Optimization

Flasks were incubated at 25 °C, 30 °C, 35 °C, and 40 °C to determine the optimum temperature for fungal growth and protein accumulation (Asghar *et al.*, 2025).

Moisture Content Optimization

Substrate moisture levels were set at 50%, 60%, 70%, and 80% (w/w). Moisture was monitored on a daily basis by weighing the flasks, and sterile distilled water was added as needed to keep the desired level (Ahmed *et al.*, 2024).

Harvesting of Biomass

After 7 days of fermentation, 100 mL of distilled water was added to each flask and thoroughly mixed. The fungal biomass was separated by vacuum filtration using Whatman No. 1 filter paper, washed repeatedly with distilled water to remove residual substrate, and oven-dried at 60 °C for 24–48 hours. Dry biomass was weighed, and biomass yield was calculated using the formula:

$$\text{Biomass Yield (g/100 g substrate)} = \frac{\text{Dry weight of biomass}}{\text{Initial substrate weight}} \times 100$$

Crude Protein Estimation

The Kjeldahl method was used to determine crude protein (Ahmed *et al.*, 2024; Abdurrazzaq *et al.*, 2025). 0.5 g of dried biomass was digested using concentrated sulfuric acid with CuSO₄ + K₂SO₄ as a catalyst. Released ammonia was distilled in a trap

containing boric acid and titrated with 0.1 N HCl. Protein content was determined as:

$$\text{Crude Protein (\%)} = \text{Total Nitrogen (\%)} \times 6.25$$

Statistical Analysis

Each experiment was performed thrice, and results were reported as mean $\pm$ standard deviation. One-way ANOVA followed by Tukey's post hoc test was performed using GraphPad Prism software. A p-value < 0.05 was considered statistically significant.

Results

Growth of *A. niger* on Different Substrates

A. niger showed successful growth on all tested substrates, including watermelon rind (WR), mango seed kernel (MSK), and their combined formulation (MSK: WR, 50:50). Initial growth of mycelia was observed within 48 hours of incubation under solid-state fermentation conditions, signifying rapid adaptation of the fungal strain to the fruit waste substrates. Mycelial density increased steadily with time, and extensive colonization and sporulation were seen in all inoculated flasks by the seventh day. Among the tested substrates, the combined MSK: WR substrate showed comparatively more uniform and dense mycelial growth, suggesting enhanced nutrient availability and improved substrate compatibility when both wastes were used together. Watermelon rind appeared to support rapid initial growth because of its higher moisture-holding capacity, whereas mango seed kernel contributed to sustained biomass accumulation, possibly due to its starch and lipid content. The combined substrate therefore provided a balanced nutritional environment conducive to fungal growth (Table 1). No visible signs of microbial contamination were observed throughout the fermentation period, confirming the effectiveness of sterilization procedures and aseptic handling during inoculation and incubation (Figure 1).

Table 1. Growth characteristics of *A. niger* on different fruit waste substrates under solid-state fermentation

Substrate	Initial Growth (48 h)	Mycelial Density (Day 7)	Sporulation	Notes
Watermelon Rind (WR)	Rapid	Moderate	Evident	High moisture, fast initial growth
Mango Seed Kernel (MSK)	Moderate	High	Evident	Starch/lipid rich, sustained biomass
MSK: WR (50:50)	Rapid	Very high	Extensive	Balanced nutrients, uniform growth



Figure 1. *Aspergillus niger* spores

Biomass Yield from Different Substrates
The yield of dry biomass differed significantly between the tested substrates ($p < 0.05$) as presented in Table 2 and Figure 2. The best biomass was obtained with the combined MSK: WR substrate ($4.28 \pm 0.21\text{g}/10\text{g}$ substrate), then mango seed kernel alone ($3.62 \pm 0.18\text{g}/10\text{g}$ substrate). Watermelon rind ($2.85 \pm 0.12\text{g}/10\text{g}$ substrate) yielded the lowest amount of biomass. The combined substrate yielded comparatively 50% more biomass than WR alone and approximately 18% more biomass than MSK alone. This increase is a sign of the synergistic effect caused by the complementary nutritional composition of the two substrates. The relatively low standard deviation values also suggest that the process of fermentation is reproducible among the replicates.

Table 2. Biomass Yield of *A. niger* on Different Substrates

Substrate	Biomass Yield (g / 10g substrate)
Watermelon rind (WR)	2.85 ± 0.12
Mango seed kernel (MSK)	3.62 ± 0.18
MSK: WR (50:50)	4.28 ± 0.21

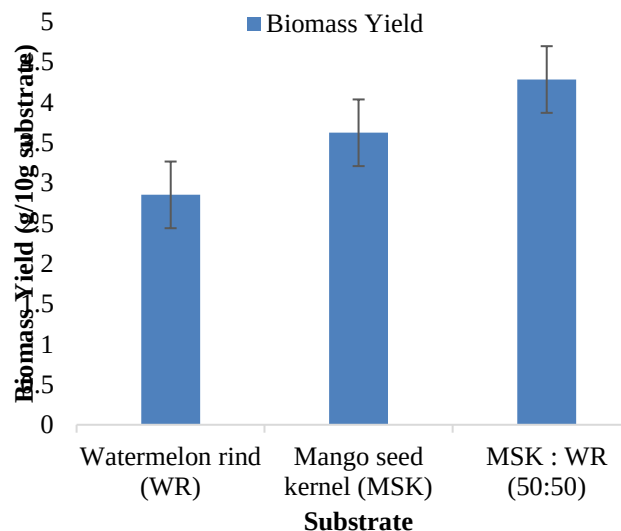


Figure 2. Biomass yield of *A. niger* grown on different substrates

Effect of pH on Biomass and Protein Production

The primary substrate pH had a considerable effect on fungal growth and SCP production ($p < 0.05$). Table 3 and Figure 3 reveal that the increase in biomass yield was recorded between pH 4.0 and pH 5.0 and culminated at pH 5.0 ($4.31 \pm 0.19\text{g}/10\text{g}$ substrate). After this optimum, there was a gradual decrease in the biomass yield as the pH values increased. Fungal growth was moderately decreased at a pH of 4.0, whereas biomass production decreased significantly at pH 7.0 and 8.0. This decrease indicates that either highly acidic or alkaline environments have adverse impacts on fungal metabolism, activity, and nutrient uptake. The identified trend proves that *A. niger* can grow and synthesize proteins optimally under solid-state fermentation in slightly acidic conditions.

Table 3. Effect of pH on Biomass Yield

pH	Biomass Yield (g / 10 g substrate)
4.0	3.21 ± 0.14
5.0	4.31 ± 0.19
6.0	3.76 ± 0.16
7.0	2.94 ± 0.13
8.0	2.18 ± 0.11

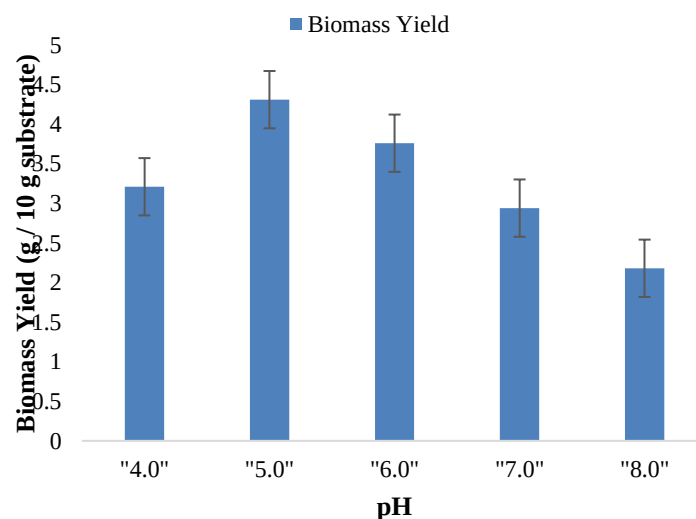


Figure 3. Effect of pH on biomass yield and protein content of *A. niger*

Effect of Temperature on SCP Production

Experiments on optimization of temperature showed that there was a significant difference in the production of biomass over the temperature range tested ($p < 0.05$). Table 4 and Figure 4 show that the highest biomass yield occurred at the temperature of 25°C ($4.34 \pm 0.20\text{g}/10\text{g}$ substrate), which is the optimal temperature under which *A. niger* can grow in a mesophilic state. At 30°C , there was a minor decrease in the biomass yield, whereas at 35°C there was a greater decrease. At 40°C minimal biomass production was observed, indicating that thermal stress and enzymatic activity are reduced at high

temperature. These findings indicate that proper incubation temperatures are necessary to optimize the SCP production process in fermentation.

Table 4. Effect of Temperature on Biomass Yield

Temperature (°C)	Biomass Yield (g / 10g substrate)
25	4.34 ± 0.20
30	3.89 ± 0.17
35	2.96 ± 0.15
40	1.87 ± 0.10

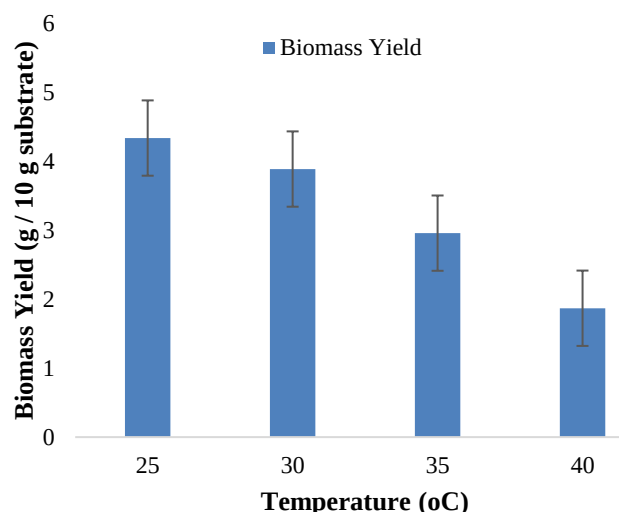


Figure 4. Effect of temperature on biomass yield

Effect of Moisture Content on Biomass Yield

Moisture content had a substantial effect on fungal metabolism, aeration of the substrate, and total SCP production. As shown in Table 5 and Figure 5, the biomass yield increased steadily with the moisture content between 50% and 70%, with a peak at 70% moisture (4.39 ± 0.22 g/10g substrate). At a low moisture content (50%), less biomass was produced, presumably because of the lack of enough water to solubilize nutrients and support microbial metabolism. On the contrary, too much moisture (80%) caused a reduction in biomass yield, which could have been caused by decreased substrate porosity and reduced oxygen diffusion. These results indicate that the optimal moisture level plays a major role in an efficient solid-state fermentation process.

Table 5. Effect of Moisture Content on Biomass Yield

Moisture Content (%)	Biomass Yield (g / 10 g substrate)
50	2.76 ± 0.13
60	3.68 ± 0.16
70	4.39 ± 0.22
80	3.02 ± 0.14

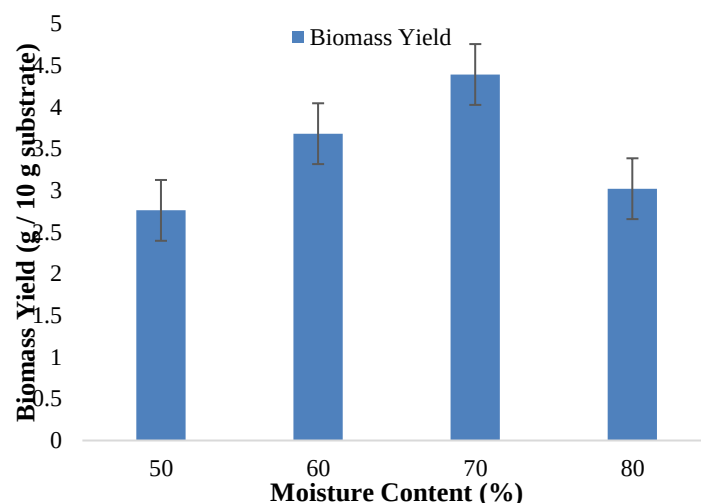


Figure 5. Effect of moisture content on SCP production

Crude Protein Content of the Produced SCP

Crude protein analysis revealed substantial enrichment of protein content in all fermented substrates. As shown in Table 6 and Figure 6, SCP produced from the combined MSK: WR substrate exhibited the highest protein concentration (51.8 ± 2.1 %), followed by mango seed kernel (44.9 ± 1.7 %) and watermelon rind (38.6 ± 1.4 %). The higher protein content observed in the combined substrate corresponds with its higher biomass yield, indicating efficient conversion of substrate nutrients into microbial protein. The protein values obtained fall within the typical range reported for fungal SCP (40–55%), confirming effective microbial protein synthesis under the optimized fermentation conditions.

Table 6. Crude Protein Content of SCP

Substrate	Crude Protein (%)
Watermelon rind	38.6 ± 1.4
Mango seed kernel	44.9 ± 1.7
MSK: WR (50:50)	51.8 ± 2.1

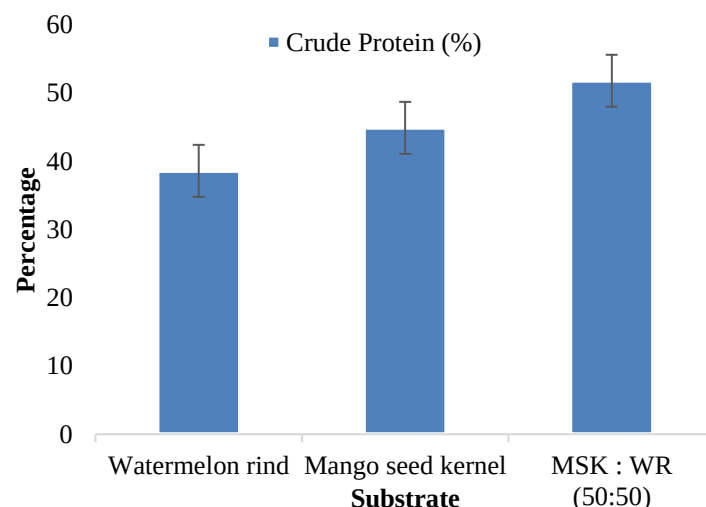


Figure 6. Crude protein content of SCP produced on different substrates

Discussion

This current research indicated that SCP could be successfully produced using *A. niger* grown on watermelon rind (WR), mango seed kernel (MSK), and a mixture of the two as a substrate in solid-state fermentation. The results are highly conclusive of the research objectives especially efficient use of fruit waste substrates, optimization of growth parameters and maximization of microbial protein yield. All in all, the findings indicate the promise of locally obtained agro-wastes as sustainable and low-cost feedstock in SCP production in Pakistan. The metabolic versatility and ability to adapt to complex plant-derived materials are supported by the fact that *A. niger* can grow well on all the substrates tested. The quick growth of mycelium in less than 48 hours is an indication of effective colonization of substrates and enzyme degradation of carbohydrate-rich wastes. Previous research has also shown similar patterns of *A. niger* growth on pineapple waste, sugarcane bagasse, and yam peels, with initial fungal colonization caused by robust extracellular enzyme systems that would hydrolyze starch, cellulose and hemicellulose ([Asghar et al., 2025](#); [Abdurrazaq et al., 2025](#)). This lack of contamination is another confirmation of the appropriateness of solid-state fermentation for the production of SCP under adequate sterilization and aseptic conditions.

The biomass yield was the highest with the combined MSK: WR formulation, and this was significantly better than that of individual substrates. This synergetic action may be attributed to the complementary nutritional characteristics of mango seed kernel and watermelon rind. The watermelon rind contains a lot of moisture, fermentable sugars, and minerals, which must have enabled fungal growth to increase rapidly at the initial stages of fermentation. Conversely, mango seed kernel has significant levels of starch and lipids, which could have enhanced sustained accumulation of biomass and protein synthesis in the later stages. ESCP shows similar gains in mixed substrates have been proposed in recent reviews, indicating that balanced carbon-nitrogen availability is key to the optimal production of microbial proteins ([Ayele et al., 2025](#); [Thiviya et al., 2025](#)). Its biomass yields can be compared to and even exceed the biomass yields obtained with other fruit-based substrates. Indicatively, [Thiviya et al. \(2021\)](#) recorded lower biomass yields of watermelon peel than papaya and pineapple wastes, which is in tandem with the comparatively lesser yield of WR alone in the current study. Nevertheless, the enhanced performance seen with the mixed substrate indicates that the strategic combination of substrates can address the drawbacks with regards to each substrate and improve the efficiency of fermentation. PH optimization showed that *A. niger* had optimal biomass growth at pH 5.0, indicating its preference for slightly acidic environments. This observation aligns with previous research that found pH between

4.5-5.5 to be the optimal pH in which fungal SCP could be produced ([Asghar et al., 2025](#); [Thiviya et al., 2022](#)). Acidic pH conditions promote the action of fungal enzymes, solubilization of nutrients and their transport across the membrane and alkaline conditions may distort cellular metabolism and protein production. The rapid reduction in biomass at elevated pH levels witnessed in the current study justifies the significance of pH monitoring in solid-state fermentation systems.

Optimization of temperature revealed that the bacterium *A. niger* grew optimally at 25°C, meaning that it was mesophilic. These findings are very similar to the data on *A. niger* being cultured on sugarcane bagasse and pineapple waste, where the highest SCP levels were observed at temperatures of 25-30°C ([Asghar et al., 2025](#); [Ahmed et al., 2024](#)). The decrease in biomass production under high temperature can be explained by thermal stress, enzyme denaturation, and membrane permeability, which, together, worsen fungal growth and protein accumulation. The level of moisture was also critical in the production of SCP, and the highest biomass output was at 70% moisture. This finding underscores the fine balance that is needed in solid-state fermentation, in that adequate moisture is necessary to facilitate diffusion of nutrients and metabolic activity, but too much moisture may lower substrate porosity and oxygen accessibility. Optimal moisture has also been observed in SCP research with fruit and agricultural wastes, which supports the overall generalizability of this observation ([Ahmed et al., 2024](#); [Thiviya et al., 2021](#)). The drop in biomass at 80 percent moisture is an additional confirmation that fungal aeration and growth efficiency are adversely affected by over-hydration.

The analysis of crude protein indicated a great enrichment of protein in the fermented biomass, especially in the joint MSK: WR substrate, which contained protein content of more than 50 percent. This is within the normal range that has been reported in fungal SCP (40-60%) and measures on par with protein levels recovered using papaya peels, potato peels and pea peels that had been previously reported ([Khan et al., 2021](#); [Khan et al., 2024](#); [Thiviya et al., 2021](#)). The increased protein composition in the mixed substrate is an indication of better use of the substrate and effective change of carbohydrates into cellular protein-rich microbial biomass. The protein enrichment obtained in this research is especially notable because the initial protein concentration of the raw materials, specifically watermelon rind, was low. This change highlights the utility of microbial fermentation in transforming low-value agro-wastes into valuable nutritious sources of proteins. In addition, the protein yields generated are competitive with standard plant-based protein sources and emphasize the possibility of fungal SCP as a partial replacement of soybean meal and other costly ingredients of animal feed as

postulated by [Sharif et al. \(2021\)](#) and [Khan et al. \(2024\)](#).

This research addresses vital issues such as food security, waste management, and sustainable protein production. Pakistan produces massive amounts of fruit waste in a year, much of which is not valorized. The effective use of watermelon rind and mango seed kernel provides a viable method of transforming local wastes that are abundant into value-added products, which are added to circular bio-economy efforts. Increased ease of fermentation, the use of a GRAS microorganism, and the utilization of cheap substrates also increase the viability of scaling this method to an industrial or semi-industrial scale. The study has some limitations even though its results are promising. The nutritional analysis was confined to crude protein content, and additional chemical analysis of amino acid composition, nucleic acid content, and digestibility is necessary to determine suitability for human consumption. Moreover, though laboratory-scale outcomes are optimistic, pilot-scale experiments and cost-effectiveness calculations are required in order to check the suitability of commercialization. By considering these factors in subsequent studies, one would make a strong argument towards production of large volumes of SCP using fruit wastes. To sum up, this current research study effectively demonstrates that watermelon rind and mango seed kernel, especially in conjunction, are good substrates in the production of SCP using *A. niger*. The streamlined fermentation conditions led to a high biomass production and high enrichment in protein, which is in line with the world efforts to come up with alternative sources of proteins that are sustainable, low cost and at the same time reduced pollution of agro-waste.

Conclusion

The current investigation was able to prove that it is possible to prepare SCP by using watermelon rind and mango seed kernel in *A. niger* under solid-state fermentation. The two substrates facilitated good fungal growth, but when they were used jointly, the biomass yield and the crude protein level were much higher, indicating that there was a synergistic effect due to the complementary nutritional value of the two substrates. Optimization of fermentation conditions indicated that fermentation was optimized at a pH of 5.0, a temperature of 25°C and a moisture content of 70 percent to produce SCP maximally. The resulting protein concentration in the mixture of the substrate was over 50, which is within the ideal protein concentration of fungal SCP and is comparable to traditional protein sources. These results affirm that locally obtained fruit wastes can be effectively transformed into value-added microbial protein, which presents a sustainable and low-cost solution to solve the protein deficiency and agro-waste management issues in Pakistan.

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Statements and Declarations

Data Availability statement

All relevant data are within the manuscript file.

Author's Contribution Statement

SH, MU, MF and KB collected data and wrote manuscript equally. SS, and IJ make final editing. TK supervised the whole research work. All authors have read the final manuscript and approve its submission.

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Conflict of interest

The investigation was undertaken without any financial conflicts of interest or any other commercial relationships that could be seen as such by any of the authors.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) have not used any ChatGPT (OpenAI) tool.



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