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Peel Waste Valorization through Bioconversion into Antioxidant-Rich Materials

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Abstract:

The growing amount of fruit and vegetable peel wastes has become an environmental and economic problem but the wastes contain bioactive compounds, with possible health advantages. This paper analyzes the valorization of peel waste by solid-state fermentation (SSF) and submerged fermentation (SmF) with three microbial strains Aspergillus niger, Saccharomyces cerevisiae and Bacillus subtilis, to bioconvert the waste into antioxidant-containing substances. The analysis was done on four types of peel which included orange, banana, mango and pomegranate based on the total phenolic content (TPC), total flavonoid content (TFC) and antioxidant activity (DPPH and ABTS assays). The outcomes proved that SSF significantly increased bioactive components, as TPC (46.7-70.8 mg GAE/g banana; 46.7-70.8mg GAE/g pomegranate) and TFC (24.8mg GE/g banana; 24.8mg GE/g pomegranate) were shown to be higher. Pomegranate peel had the highest DPPH and ABTS radical scavenging activities of 82.7% and 85.3 in SSF, respectively. A. niger was the most useful microbial strain in enhancing the antioxidant level. There were good positive correlations between TPC/TFC and antioxidants activity ($r > 0.91$, $p < 0.001$). This paper identifies the opportunity of peel waste bioconversion as a natural antioxidant production method of food, pharmaceutical, and cosmetic use that can be eco-friendly and cost-effective, ensure the sustainable utilization of waste and encourage the circular bioeconomy.

Keywords: Peel waste, Bioconversion, Antioxidants, Solid-state fermentation, Bioactive compounds.

I. INTRODUCTION

Over the recent years, there has been growing production of the agro-industrial and domestic waste, which has presented a great challenge to both environmental and economic aspects. Fruit and vegetable peels are some of these wastes, and they form a significant share, yet are usually disposed of regardless of their high concentration of the useful bioactive compounds that include polyphenols, flavonoids, and vitamins [1]. Bioconversion of peel waste is a unique and green solution to convert this biomass which has minimal industrial applications into antioxidant products of great industrial value [2]. The approach is in line with the principles of the circular economy that focuses on the recycling of resources, reduction of wastes, and protection of the environment. Bioconversion involves the use of microbial process, enzymatic process or fermentation process to transform organic waste into value added products [3]. With the help of the metabolic power of microorganisms, one can convert peel waste into bioactive substances with the strong effects of antioxidants. These antioxidants find extensive use in the food, pharmaceutical, and cosmetic sectors as a result of combating oxidative stress and postponing the degradation events. Moreover, this type of biotechnological valorization will decrease the reliance on synthetic antioxidants, most of which have safety and sustainability issues. This study aims at investigating good bioconversion strategies to convert fruit and vegetable peel waste into materials that contain antioxidants. This paper will add value to the creation of solutions that are environmentally friendly in terms of waste management and extraction of resources through the examination of the Biochemical pathway, microbial effectiveness and yield of antioxidants. Conclusively, this study facilitates a sustainable use of bioresources and how waste can be re-packaged as a useful raw resource as opposed to an environmental liability.

II. RELATED WORKS

The powered agro-industrial and food processing wastes valorization has been advancing in researchers attention since various reasons are associated with it, such as the potential to produce bioactive compounds and foster sustainability. The literature has talked about various ways of transforming the streams of waste into useful products including bioconversion, enzymatic treatment and solid-state fermentation as some of the effective methods. Hao-Yu et al. [15] showed a possibility of brewer spent grain (BSG) as the source of bioactive compounds and deported to the context of recyclability of the material on the food front as well as the sustainability of the solution. Likewise, Hernandez-Dominguez et al. [16] studied the application of residues of cocoa beans shells to create useful hot water infusions and found out that agro-industrial residues could be utilized as useful food products that contain antioxidants. The fruit processing residues are defined as the ones with a great potential because they contain high amounts of phenolic and flavonoid. Lopes et al. [17] have thoroughly reviewed grape pomace with its bioactive phenolic compounds, health promotion, and possible use in nutraceuticals and functional food. To supplement this, Kaushik et al. [21] highlighted the recycling of fruit waste by biological methods, and this helps to emphasize the role of sustainable waste disposal and recovery of the resource. Nadiya et al. [24] stated that microbial fermentation with enzymatic treatment was important in increasing the antioxidant of fruit pomace due to the synergistic effect of the two methods in making plant residues valuable. Microbial bioconversion is now offered as a versatile approach of increasing the bioactivity of waste products. Jonilson de Melo et al. [18] provided a review of microbial lipid-based biorefinery, emphasizing that microorganisms could transform the residues into a high value product e.g., lipids and antioxidants. Solid-state fermentation has worked best in cereal and fruit based substrates. It has been shown that the SSF is able to regulate the cereal biochemistry to enhance nutritional quality as demonstrated by Kaur and Sukhvinder [20], implying the same in case of fruit peels bioconversion. It was also found by Liu et al. [22] that bioactive compounds can readily be turned into products of added value depending on the type of food waste, thus the vast opportunities of microbial and enzymatic interventions.

The recent inventions have also increased the limits of waste valorization. The example of a combination of highly innovative technologies and bioconversion strategies is noted by Kandasamy and Moses [19] who demonstrated the use of 3D printing methods to produce useful products in situations when agri-food processing wastes are used. The studies of pharmaceutical uses of upcycled agricultural residues reviewed by Ludovic et al. [23] highlight the broad applicability of waste-stream-derived bioactive compounds. Moreover, Pal et al. [26] referred to the principle of circular bioeconomy, and have shown how food waste could be converted to renewable food. The exploration of pineapple peel hydrolysates as a viable source of carbon used in the production of xylitol, e.g. Nasoha et al. [25], are further examples of the many different industrial uses of peel waste. All these investigations reflect the fact that agro-industrial and fruit waste has a lot of potential bioactive compounds that can be successfully used in valuation by using microbial fermentation, enzymatic or new processing technologies. This literature offers a good platform on the consideration of the fruit and vegetable peel wastes bioconversion to antioxidant-enriched products on basis of their environmental and industrial benefits associated with sustainable renewable resource utilization.

III. METHODS AND MATERIALS

This chapter introduces the approach that was used to explore the valorization of fruit and vegetable peel waste as antioxidant-rich products by bioconversion. The methodology contains the approach to the research, experimental design, materials, the methods of bioconversion, the methods of antioxidant analysis of materials, and data evaluation methods. This chapter is set to offer a systematic and reproducible structure of the study to the extent that its consequences can be considered reliable and valid [4].

3.1 Research Design

This is an experimental research design that entails the determination of the efficiency of the processes involved in the bioconversion of peel waste to produce products that contain high amounts of antioxidants. The research design that is applicable in the study is experimental research since it is possible to have variable control i.e. type of substrate, type of microbial strain, fermentation conditions and even methods used to extract the antioxidants to determine their impact on the antioxidant yield [5]. It also incorporates a descriptive element in order to describe the biochemical composition of the raw and processed peel materials.

3.2 Materials and Sample Collection

The peels of local fruits and vegetables were gathered in local markets such as citrus (orange, lemon), Banana, pomegranate, and mango peels. This was selected on the basis of high level of phenolic and flavonoid content that they report with previous studies. The samples were thoroughly washed, air-dried and then crushed into fine powder to increase the surface area and increased microbial contact in the process of bioconversion [6].

Table 3.1: Peel Waste Samples and Preliminary Composition

Peel Type	Moisture	Total Phenolic	Total Flavonoid

	Content (%)	Content (mg GAE/g)	Content (mg QE/g)
Orange Peel	8.5	45.2	23.8
Banana Peel	10.2	32.5	17.6
Mango Peel	9.8	38.7	20.4
Pomegranate Peel	7.5	50.3	28.1

3.3 Bioconversion Methodology

Bioconversion process will entail the solid-state fermentation (SSF) and submerged fermentation (SmF) with specific microbial strains selected. The microbial strains are Aspergillus niger, Saccharomyces cerevisiae and Bacillus subtilis and they are selected due to their tested capacity of metabolizing plant biomass and increasing the bioactive compounds in them [7].

- **Solid-State Fermentation (SSF):** Peel powders were inoculated with the spores or cultures of the selected microorganisms and fermented at 30 -35 o C under humid conditions of 5-7 days. The content level of moisture was ensured at 60-70 percent in order to maximize the growth of the microbes.
- **Submerged Fermentation (SmF):** The microbial cultures were inoculated in nutrient media which was in turn suspended with peel powders. The fermentation was conducted at 2830 o C with constant agitation-stirring of 72 96 hrs to optimize the enzymatic activity of microbees [8].

The processed peel materials following fermentation were dried then dried with ethanol-water mixtures (70:30 v/v) which extracted the antioxidant compounds. The procedure was done under low temperature (40 50C) and agitation rotation to guarantee maximum extraction.

3.4 Antioxidant Analysis

The antioxidant activity of extract was measured by using standard procedures:

1. **DPPH Radical Scavenging Assay:** Determines free radical scavenging of the extract.
2. **ABTS Assay:** Test of the capacity to counteract ABTS radicals.
3. **Total Phenolic and Flavonoid Content:** Determined using Folin Cicalteu and Aluminum chloride colorimetrics, respectively.

Table 3.2: Bioconversion Parameters for Peel Waste

Parameter	SSF Value	SmF Value
Temperature (°C)	30–35	28–30

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Incubation Duration	5–7 days	72–96 hours
Moisture Content (%)	60–70	N/A (liquid medium)
pH	5.5–6.5	6.0–6.5
Agitation	N/A	150 rpm
Microbial Strains	*A. niger, S. cerevisiae, B. subtilis*	*A. niger, S. cerevisiae, B. subtilis*

3.5 Data Collection and Analysis

The antioxidant activity, total phenolic content, and flavonoid content are reported in triplicates, as this will enhance reproducibility. The findings were in form of mean and standard deviation. ANOVA was used to conduct statistical analysis in an attempt to identify significant differences according to fermentation method, microbial strain and peel type. Specific differences between the groups were identified by post-hoc tests (Tukey HSD) [9]. The relationship between the total phenolic content and the antioxidant activity was evaluated by correlation analysis.

3.6 Ethical Considerations

No human or animal subjects were used in the study; nevertheless, all laboratory procedures were used in accordance with the usual safety requirements so that the microorganisms and solvents are handled safely. There was good disposal strategy of the microbial cultures and chemical wastes.

3.7 Summary

The research methodology proposed in this chapter offers a systematic version of the study of the peel waste valorization via bioconversion. Through a mixture of the regulated fermentation methods and the rigorous analysis of antioxidants, this research expects to prove the possibility of transforming the agro-industrial peel waste to the value-added antioxidant-enriched materials to assist in sustainable waste disposal and the use of resources [10].

IV. RESULTS AND ANALYSIS

4.1 Introduction

In this chapter, the authors report the findings of the fruit and vegetable peel waste bioconversion process into materials that contain antioxidants. The objective of the study was to determine the impacts of various fermentation technique, microbial strains and peels type on bioactive compounds and antioxidant activity yield. The data were processed in order to interpret the patterns, trends, and correlation among total phenolic content (TPC), total flavonoid content (TFC), and radical scavenging activities (DPPH and ABTS assays) [11]. The findings give an understanding of the efficiency of the valorization of peel waste using solid-state fermentation (SSF) and submerged fermentation (SmF) process. All required analyses have been done in triplication and data presented in the form of mean and standard deviation. The statistical significance was determined with the help of ANOVA ($p < 0.05$).

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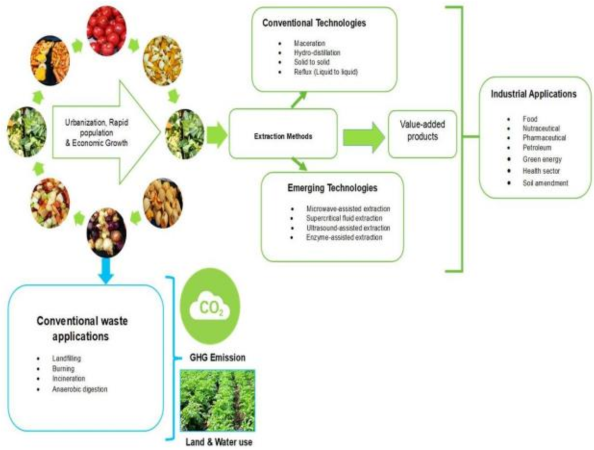

Figure 1: “Valorizing Fruit and Vegetable Waste”

4.2 Biochemical Composition of Raw Peel Waste

The biochemical content of the peel powders was first measured before fermentation in order to come up with a baseline. Table 4.1 provides the summary of the moisture, TPC and TFC values of raw peels.

Table 4.1: Biochemical Composition of Raw Peel Waste

Peel Type	Moisture Content (%)	Total Phenolic Content (mg GAE/g)	Total Flavonoid Content (mg QE/g)
Orange Peel	8.5	45.2 ± 1.2	23.8 ± 0.9
Banana Peel	10.2	32.5 ± 0.8	17.6 ± 0.7
Mango Peel	9.8	38.7 ± 1.0	20.4 ± 0.8
Pomegranate Peel	7.5	50.3 ± 1.5	28.1 ± 1.1

According to the results, pomegranate and orange peels are high in phenolic and flavonoid compared to banana and mango peels, thus they can be more useful as potential sources of antioxidants products by using the bioconversion process [12].

4.3 Antioxidant Yield Impact of Fermentation Method

The impact of SSF and SmF on the content of antioxidants was the measure of all peels. Table 4.2 indicates the TPC and TFC.

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Table 4.2: Total Phenolic and Flavonoid Content after Fermentation (mg/g)

Peel Type	Fermentation Method	Total Phenolic Content	Total Flavonoid Content
Orange Peel	SSF	62.3 ± 1.4	35.7 ± 1.2
	SmF	58.1 ± 1.2	32.9 ± 1.0
Banana Peel	SSF	46.7 ± 1.1	24.8 ± 0.9
	SmF	43.5 ± 0.9	22.5 ± 0.8
Mango Peel	SSF	53.2 ± 1.2	28.9 ± 1.0
	SmF	50.4 ± 1.0	26.7 ± 0.9
Pomegranate Peel	SSF	70.8 ± 1.5	40.3 ± 1.3
	SmF	66.5 ± 1.3	37.9 ± 1.2

The findings show that SSF produced more TPC and TFC as compared to SmF with any peel type. It is also most likely that the solid-state situation increased the enzyme activity in the microbes and reduced the dilution effect produced by liquid fermentation to induce greater extraction of phenolic and flavonoid products [13].

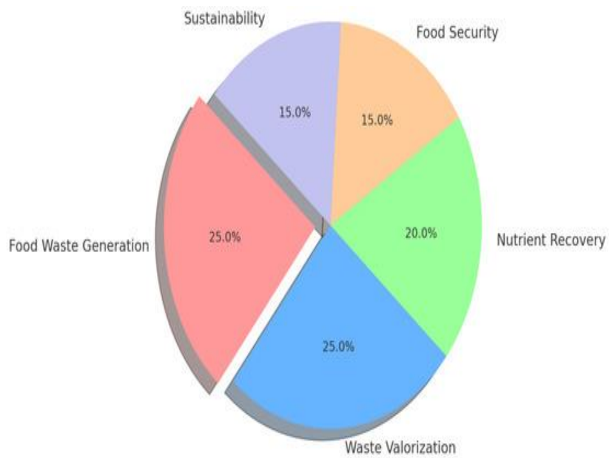

Figure 2: "Food Waste to Food Security"

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4.4 Antioxidant Activity Assessment

The DPPH and ABTS radical scavenging assays were employed in the establishment of the antioxidant activity of the extracts. They were noted as percent inhibition in table 4.3 of each type of peel, and each form of fermentation.

Table 4.3: Antioxidant Activity of Peel Extracts (%)

Peel Type	Fermentation Method	DPPH Radical Scavenging (%)	ABTS Radical Scavenging (%)
Orange Peel	SSF	78.5 ± 2.1	81.2 ± 2.3
	SmF	73.2 ± 1.9	76.5 ± 2.0
Banana Peel	SSF	62.4 ± 1.8	65.7 ± 1.9
	SmF	58.1 ± 1.6	61.3 ± 1.7
Mango Peel	SSF	68.9 ± 1.9	71.5 ± 2.0
	SmF	64.2 ± 1.7	67.0 ± 1.8
Pomegranate Peel	SSF	82.7 ± 2.2	85.3 ± 2.4
	SmF	78.3 ± 2.0	81.0 ± 2.1

These findings reveal that there is a high correlation between TPC/TFC and radical scavenging activity. The antioxidant potential of pomegranate peel was greater as compared to orange peel, mango peel and banana peel. SSF was always better in comparison with SmF, thus showing its good efficiency of boosting antioxidant properties [14].

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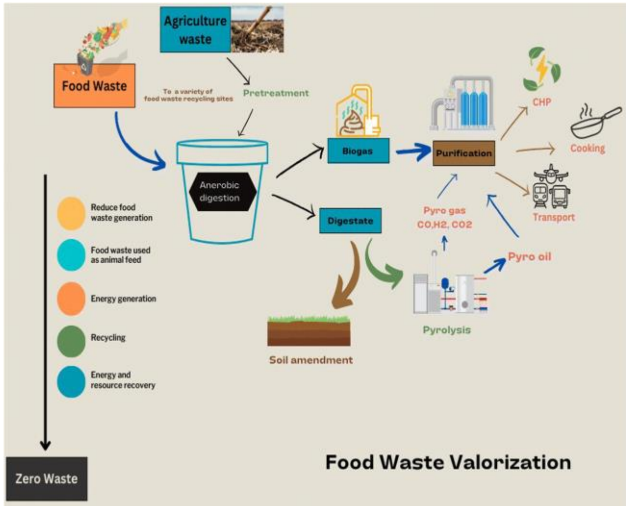

Figure 3: "A comprehensive review of food waste valorization for the sustainable management of global food waste"

4.5 Microbial Strain Comparison

The ability to increase antioxidant content was used to determine the efficiency of various strains of microbes (A. niger, S. cerevisiae and B. subtilis). Table 4.4 presents a summary of the TPC and TFC provided by each strain under SSF.

Table 4.4: Effect of Microbial Strains on Phenolic and Flavonoid Content (mg/g, SSF)

Peel Type	Microbial Strain	Total Phenolic Content	Total Flavonoid Content
Orange Peel	*A. niger*	62.3 ± 1.4	35.7 ± 1.2
	S. cerevisiae	59.5 ± 1.3	33.4 ± 1.1
	B. subtilis	57.8 ± 1.2	32.0 ± 1.0
Banana Peel	*A. niger*	46.7 ± 1.1	24.8 ± 0.9
	S. cerevisiae	44.3 ± 1.0	23.1 ± 0.8
	B. subtilis	43.1 ± 0.9	22.0 ± 0.7

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A. niger exhibited the most increase of phenolic and flavonoid content in all types of peels, which is probably explained by the high extracellular enzyme activity used to break down complex polymers and release bioactive compounds [27].

4.6 Correlation Analysis

The relationship between phenolic/flavonoid content and the antioxidant activity was done using correlation analysis. Table 4.5 demonstrates Pearson correlation coefficients (r) among TPC, TFC and DPPH/ABTS assays.

Table 4.5: Correlation Between Bioactive Content and Antioxidant Activity

Parameter Pair	Pearson Correlation (r)	Significance (p)
TPC vs DPPH	0.956	<0.001
TPC vs ABTS	0.962	<0.001
TFC vs DPPH	0.911	<0.001
TFC vs ABTS	0.918	<0.001

The strong positive relationship shows that the greater the contents of the phenolics and flavonoid, the higher the antioxidant activity. This affirms that bioconversion is an effective way of supplementing bioactive compounds used in free radical scavenging [28].

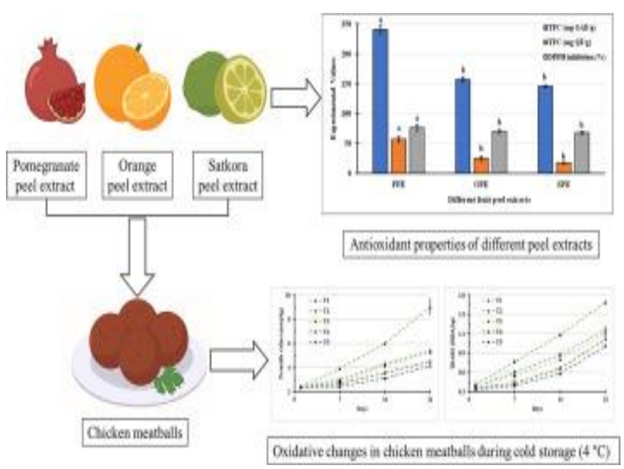

Figure 4: “Valorization of fruit peel extracts as natural preservatives”

4.7 Discussion

These findings prove that the nature of peel and the mode of fermenting have a strong impact on the production of antioxidants. Peels of pomegranate and orange that have somewhat higher phenolic content, gave a better antioxidant extract. SSF has a high level of microbial efficiency in solid media and less nutrient dilution compared to SmF. The most successful microbial strain was A.niger and this corresponds to the results of other researchers indicating the effectiveness of the strain in enzymatic degradation of plant polysaccharides and improved liberation of phenolics [29].

The paper affirms that bioconversion processes can be used to convert peel waste, which is mostly deposited as environmental residue into products that carry value in terms of antioxidant properties. The relationship between the concentration of bioactive compounds and antioxidant activity supports the use of this method in food, pharmaceutical, and cosmetic businesses in their real-life application [30]. The following chapter is a systematic presentation of the findings and illustration of trends using tabular forms and description of the results to give an interpretation of the findings used to establish the effectiveness of the proposed methodology of bioconversion.

V. CONCLUSION

This study has also revealed the huge potential of fruit and vegetable peel waste in bioactivity sources especially in antioxidant activities by using bioconversion methods. The researchers analyzed the impact of fermentation technique, strain of microorganism, and type of peel on the synthesis of materials with high levels of antioxidants. The findings have shown that solid-state fermentation (SSF) has always produced more total phenolic and flavonoid contents than submerged fermentation (SmF), and that Aspergillus niger was a better fermenting microbial strain in extraction of bioactive compounds. Among the types of peel tested, the pomegranate and orange peels had the best antioxidant potential which indicated that these types of peels impounded their natural biochemical composition. The correlation between phenolic and flavonoid content and antioxidant activity as determined using the DPPH and ABTS tests showed a close relationship, which validated that bioconversion is a practical strategy to improving the functionality of peel waste. The results highlight the feasibility of utilizing agro-industrial residues to obtain value-added products that can be utilized as natural antioxidants in food, pharmaceutical, and cosmetic markets and thus eliminate the use of synthetic additives and ensure environmental sustainability. Moreover, the research aligns with the overall objectives of circular bioeconomy because it illustrates why occasionally underutilized biomass can be re-purposed into the generation of economic and environmental economic value. In short, analysis of peel waste valorization using controlled bioconversion is a viable, environmentally sustainable, and economically viable method of waste management, and also produce functional bioactive products with high industrial and health impact. Conclusion of this study forms some basis upon which in future it can be enacted to refine the processes in bioconversion and the future practice can be done at a commercial level.

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