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ORIGINAL ARTICLE

Utilization of Phytochemicals and Antioxidants from Orange and Pomegranate Peel Waste for Combined Fortification in Pharmaceutical Products: A Sustainable Waste Management Approach

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ABSTRACT

The rising interest in natural health products has highlighted the need for sustainable alternatives to synthetic additives in the food industry. Citrus and pomegranate peels, often discarded as waste, are rich in bioactive compounds that could enhance the nutritional quality of functional foods. This study investigates the phytochemical composition and antioxidant properties of orange and pomegranate peel powders, assessing their potential applications in health-promoting products like immunity syrup. FTIR analysis revealed various functional groups in both peel powders, indicating the presence of beneficial phytochemicals. Orange peel exhibited primary aliphatic amines, phenolic compounds, and fluoro compounds, while pomegranate peel contained alkynes and sulfate groups. Qualitative phytochemical analysis showed the presence of tannins, flavonoids, and alkaloids in both peels. Quantitative evaluations using the DPPH radical scavenging assay demonstrated that pomegranate peel powder had a higher antioxidant activity compared to orange peel powder. The total phenolic content (TPC) was significantly greater in pomegranate peel than in orange peel, whereas orange peel displayed a slightly higher total flavonoid content (TFC) compared to pomegranate peels. Incorporating these peel powders into an immunity syrup demonstrated promising stability and sensory attributes, reflecting the potential of utilizing citrus and pomegranate peels as natural health products and promoting waste reduction in the food industry.

Keywords: Antioxidants, Fortified syrup, Fruit peel waste, orange peel, Pomegranate peel

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INTRODUCTION

The global fruit processing industry generates over 0.5 billion tons of fruit waste annually, with fruit peels accounting for a significant portion of this waste [1]. Commonly discarded as agro-waste, fruit peels are rich in macronutrients, micronutrients, and bioactive compounds, making them valuable resources for applications in agriculture and the pharmaceutical industry [2] However, inadequate management practices for fruit waste has lead to environmental degradation and pollution, highlighting the need for

effective strategies to utilize these by-products. For instance, fruit peels have been found to improve soil fertility, regulate pH, and serve as natural fertilizers, enhancing crop production and reducing environmental pollutants [1]. In horticultural crops, 20-30% of the total product weight is waste, including peels, seeds, and pomace, all of which are highly valuable in bioactive compounds such as carotenoids, enzymes, polyphenols, and essential oils [3] [2]. The rising global population and shifting dietary habits have significantly increased the demand for horticultural crops, leading to a corresponding rise in waste generation (FAO, 2021). In India alone, approximately 50 million tons of fruit and vegetable waste are produced annually, contributing to pollution and environmental degradation [4]. Fruit peels, however, present a solution to these challenges. Recent studies have demonstrated that fruit peels are reservoirs of antimicrobial, antioxidant, and antiviral agents, making them suitable for pharmaceutical applications [5]. These peels, containing various active compounds with insecticidal and antifungal properties, can also be used in formulations targeting plant pathogens [6]. Importantly, utilizing fruit peel waste not only mitigates pollution but also contributes to the development of value-added products in food, pharmaceutical, and cosmetic industries [7].

Among the most promising types of fruit waste, orange and pomegranate peels stand out due to their high content of bioactive compounds. Orange peels, which make up 30-40% of the total fruit weight, are rich in Vitamin C, flavonoids, phenolic compounds, and carotenoids, all of which exhibit potent antioxidant properties [8]. These compounds protect cells from oxidative damage and may reduce the risk of chronic diseases. Globally, orange production generates 25 to 57 million tons of waste annually, making the sustainable utilization of this waste an urgent priority [7]. Similarly, pomegranate peel waste, which accounts for approximately 1.6 billion tons globally, is a dense source of antioxidants, polyphenols, and dietary fibers [9]. Despite being non-edible, pomegranate peels are known for their medicinal properties and have been shown to contain higher concentrations of bioactive compounds than the fruit's edible parts [10]. These peels are particularly rich in pharmacologically active compounds that are valuable for the development of nutraceuticals and food additives [11]. The aim of this research is to explore the potential of combined fortification of orange and pomegranate peel waste in pharmaceutical products. By utilising the potent phytochemicals and antioxidants present in these fruit peels, this study seeks to contribute to sustainable waste management practices while creating innovative, health-promoting pharmaceutical applications.

MATERIAL AND METHODS

Fresh orange and pomegranate fruits were procured from the local market. The peels were collected and processed into powder form. All chemicals and reagents used in the study were of analytical grade.

Preparation of Sample

Orange and pomegranate fruits were thoroughly washed, and the peels were collected. The peels were processed separately and stored in sealed containers. The peels were dried using a tray dryer and then ground into powder. The resulting peel powder was sieved and stored in airtight containers. Extracts from both orange and pomegranate peel powders were prepared at a 10:10 ratio with distilled water for subsequent analytical evaluations.

Proximate Analysis

The proximate analysis of orange peel and pomegranate peel powder was determined using AOAC method. Moisture content, ash, fat, crude fiber, proteins and carbohydrates of both peel powder samples were determined.

Biochemical Analysis

The pH, color, bulk density, tapped density, Hausner ratio, and compressibility index of the orange and pomegranate peel powders were determined. Bulk density and tapped density measurements followed the protocol outlined [12], with slight modifications. In this method, 5g of the powdered sample was placed into a 50 ml graduated cylinder. The initial volume was recorded, and all readings were performed in triplicate to ensure accuracy. The bulk density was calculated using the equation: Bulk density = Weight of sample / Volume of sample. For tapped density, 5g of the powder was similarly placed in a 50 ml cylinder, but after 30 taps, the volume occupied by the sample was recorded. Tapped density was calculated as: Tapped density = Weight of sample / Volume of sample after tapping. The Hausner ratio and compressibility index were calculated following the method described by Gupta et al. (2015) [13]. The Hausner ratio was derived using the formula: Hausner ratio = Tapped density / Bulk density. The compressibility index was calculated using the formula: Compressibility index = (Tapped density - Bulk density) × 100 / Tapped density

Functional Attributes

Swelling Index/ Capacity

The swelling index method, as described by Zaker et al. (2017) [14], was used to determine the swelling capacity of the sample. A 0.5g portion of the sample was weighed into a 50 ml measuring cylinder, and deionized water was added to reach a total volume of 50 ml. The mixture was stirred thoroughly and allowed to equilibrate for 24 hours at room temperature. After equilibration, the weight of the swollen sample was recorded. The swelling capacity was calculated as the ratio of the weight of the swollen sample to the weight of the dry sample and was expressed in g/ml.

Water Retention Capacity

Water retention capacity was evaluated following the method described by Abou-Arab et al. (2017) [15]. In this procedure, 1g of the sample was mixed with 30 ml of deionized water in a 50 ml centrifuge tube. The slurry was allowed to settle for 10 minutes before being centrifuged at 2000 rpm for 15 minutes. After centrifugation, the supernatant was drained, and the wet precipitate was weighed. Water retention capacity was expressed in g/ml.

Water Absorption Capacity

Water absorption capacity was determined using the method described by Dias et al. (2020) [12]. In this procedure, 1g of the sample was mixed with 10 ml of deionized water and vortexed for 30 seconds. The mixture was allowed to stand at room temperature for 30 minutes before being centrifuged at 3000 rpm for 30 minutes. The volume of the supernatant was recorded. Water absorption capacity was calculated as the difference between the initial volume of water added and the volume of supernatant, and was expressed in g/ml.

Index of Water Absorption Capacity

The Water Absorption Index (WAI) was determined following the method described by Mall et al. (2023) [16]. A blank centrifuge tube was weighed, and 0.50 g of the sample was mixed with 6 ml of deionized water in the tube. The tubes were sealed and allowed to stand at room temperature for 20 minutes. Afterward, the tubes were centrifuged at 1050 rpm for 10 minutes. The supernatant was drained, and the wet pellet (residue) was weighed. The WAI was calculated using the formula: WAI = (weight of centrifuge tube and sample – weight of centrifuge tube) / weight of sample. WAI was expressed in g/ml.

Oil Holding Capacity

Oil Holding Capacity (OHC) was evaluated using the method described by Armel et al. (2021) [17] with slight modifications. In this procedure, 0.5 g of the sample was mixed with 3 ml of rice bran oil. The mixture was agitated for a few seconds and then centrifuged at 3000 rpm for 30 minutes. The supernatant was drained, and the wet sample pellet was weighed. OHC was calculated using the formula: OHC = [(M1 - M0) / M0] × 100, where M1 is the weight of the pellet and M0 is the weight of the sample taken. OHC was expressed in g/ml.

Oil Absorption Capacity

Oil Absorption Capacity (OAC) was determined using the method described by Hu and Zhao (2018) [18] with slight modifications. In this procedure, 0.50 g of the sample was mixed with 10 ml of rice bran oil and incubated at room temperature for 24 hours. The sample mixture was then centrifuged at 1050 rpm for 10 minutes. The supernatant was discarded, and the wet pellet (residue) was collected and weighed. OAC was calculated using the formula: OAC = (W1 - W2) / W1, where W1 is the weight of the sample and W2 is the weight of the sample residue. OAC was expressed in g/ml.

Oil Retention Capacity

Oil Retention Capacity (ORC) was evaluated using the method described by Bader et al. (2022) [19] with slight modifications. One gram of the sample was mixed with 10 ml of rice bran oil and vortexed for 30 seconds. The mixture was then allowed to stand at room temperature for 30 minutes. After this, the sample was centrifuged at 3000 rpm for 30 minutes, and the volume of the supernatant was recorded. ORC was expressed in g/ml.

Emulsification Capacity and Emulsification Stability

Emulsification capacity and stability were assessed using the method described by Bader et al. (2022) [19] with slight modifications. For the emulsification capacity evaluation, 5 g of the sample was mixed with 10 ml of distilled water (DW) and 5 ml of rice bran oil. The mixture was vortexed for 1 minute and subsequently centrifuged at 1100 rpm for 5 minutes. The height of the emulsified layer and the total height of the contents in the tube were measured. The emulsification capacity was calculated using the following formula:

Emulsification Capacity= (Total Height of Contents/ Height of Emulsified Layer)×10.

To determine emulsification stability, the emulsions were reheated at 80°C for 30 minutes and then centrifuged at 1000 rpm for 5 minutes.

The emulsification stability was calculated using the formula:
Emulsification Stability=(Height of Total Contents before Heating/Height of Emulsified Layer after Heatin g)×100. Both emulsification capacity and stability were expressed in g/ml.

Foaming Capacity and Foaming Stability

Foaming capacity and stability were determined using the method described by Dias et al. (2020) [12] with slight modifications. In this method, 5 g of the sample was mixed with 100 ml of distilled water (DW). The resulting suspension was vigorously stirred for 2 minutes. Both the initial and final volumes of the foam were recorded. The foaming capacity was calculated using the formula:
Foaming capacity = (Volume 2-Volume 1)/ Volume 1) x 100, where Volume 1 and Volume 2 are initial and final volume after the sample was whipped.
Foaming stability was assessed by measuring the foam volume that remained after 6 hours. The initial and final foam volumes were observed, and the foaming stability was calculated using the formula:
Foaming stability = (Volume 2-Volume 1)/ Volume 1) x 100.
Both Foaming capacity and stability are expressed in g/cm^{-3}.

Analytical Evaluation

UV-Vis Spectrophotometer

The peel powders of orange and pomegranate were analyzed using a Jasco V-730 UV-Vis Spectrophotometer. A 10 mg sample of each peel powder was mixed with 10 ml of distilled water, with no further dilution. The UV spectra (λmax) were recorded within the normal UV-visible wavelength range of 900-1100 nm, and the readings were expressed in nanometers (nm).

Fourier Transform Infrared Spectroscopy

The peel powders of orange and pomegranate were analyzed using a Jasco FT/IR-4600 Fourier Transform Infrared Spectrophotometer (FTIR). A small quantity of each sample was placed on ATR. Background spectra were recorded first, followed by the spectra of the orange and pomegranate peel powders. FTIR readings were expressed in cm^{-1}.

Qualitative Phytochemical Analysis

Phytochemical analysis of orange and pomegranate peel powders was conducted following the method described by K & Ganesan et al. (2023) [20] with slight modifications. For qualitative estimation, 50 mg of each sample was mixed with 50 ml of distilled water to prepare the extract. Phytochemical analysis of orange and pomegranate peel powder extracts involved several tests for specific compounds. The tannin test (lead acetate test) was conducted by adding a few drops of 1% lead acetate to 2 ml of the extract, where yellowish precipitation indicated the presence of tannins. For the saponin test, 2 ml of extract mixed with 1.5 ml of distilled water was shaken, and the formation of foam confirmed saponins. The flavonoid test involved adding 2 ml of extract to 2N NaOH, resulting in a yellow color that indicated flavonoids. The phenol test (Ferric chloride test) was performed by adding 2 ml of extract and a few drops of 5% $FeCl_3$, with a bluish-black or greenish-black color indicating phenols. The coumarin test involved mixing 1 ml of extract with 2 ml of 10% NaOH, where yellow color formation confirmed coumarins. The quinone test was conducted by adding 1 ml of concentrated H_2SO_4 to 1 ml of extract, resulting in a red color that indicated quinones. For the phlobatannin test, a few drops of 2% HCl were added to 1.5 ml of extract, producing a reddish-pink color, confirming phlobatannins. The glycosides test (Keller-Killani test) involved adding 1 ml of extract to 2.5 ml of glacial acetic acid, a few drops of 5% $FeCl_3$, and 1 ml of concentrated H_2SO_4; a brown ring at the interface indicated glycosides. The alkaloids test was performed by adding a few drops of dilute HCl to 2 ml of extract followed by 2 ml of Mayer's reagent, with white to yellow precipitation indicating alkaloids. Lastly, the steroids test involved adding a few drops of concentrated H_2SO_4 to 2 ml of extract, where red color formation indicated the presence of steroids.

Quantitative Evaluation

Antioxidant activity evaluation through DPPH

Antioxidant activity of orange and pomegranate peel powder was evaluated using the DPPH assay based on the method described by Sado et al. (2022) [21], with slight modifications. Ascorbic acid was used as the standard, with a concentration of 50 µg/ml. A stock solution of 25 µg/ml was prepared by dissolving 1.25 mg of ascorbic acid in 50 ml of distilled water. For the assay, 1 ml of each sample and standard concentration was mixed with 4 ml of 0.1 mM DPPH solution in an Eppendorf tube. Standard DPPH concentrations were 5, 10, 15, 20, and 25 µg/ml, with all readings taken in triplicate. After 30 minutes of incubation, absorbance was measured at 517 nm using a UV-Vis spectrophotometer. The rapid scavenging activity was calculated using the formula:
Scavenging Activity = [(Blank-Sample)/Blank] x100.

Antioxidant activity evaluation through TPC

Antioxidant activity of orange and pomegranate peel powder was evaluated using the Total Phenolic Content (TPC) assay, following the method by Ghasemi et al. (2009) [22] with slight modifications. Gallic acid served as the standard, with a concentration of 50 µg/ml prepared by dissolving 0.5 mg of gallic acid in 20 ml of distilled water to create a 25 µg/ml stock solution. For the assay, 1 ml of each sample and standard concentration was mixed with 2.5 ml of 0.2 N Folin-Ciocalteu (FC) reagent in a test tube, followed by the addition of 7.5% Na2CO3. Standard concentrations for TPC were 5, 10, 15, 20, and 25 µg/ml, with all readings taken in triplicate. After 30 minutes of incubation, absorbance was measured at 765 nm using a UV-Vis spectrophotometer.

Antioxidant activity evaluation through TFC

Antioxidant activity of orange and pomegranate peel powder was evaluated using the Total Flavonoid Content (TFC) assay, following the method by Hegazy & Ibrahium (2012) [23] with slight modifications. Quercetin served as the standard at a concentration of 50 µg/ml, prepared by dissolving 2.5 g of quercetin in 50 ml of distilled water to create a 25 µg/ml stock solution. For the assay, 1 ml of each sample and standard concentration was mixed with 0.1 mM quercetin, followed by the addition of 5% NaNO2, 10% AlCl3, and 1 ml of NaOH. Standard concentrations for TFC were 5, 10, 15, 20, and 25 µg/ml. After 15 minutes of incubation, absorbance was measured at 510 nm using a UV-Vis spectrophotometer.

Fortification

Orange and pomegranate peel powders were incorporated into a natural immunity syrup, following the method of Nirmal et al. (2020) [24] with slight modifications. The control syrup was prepared without peel powders, while the sample syrup was fortified with these powders. The immunity syrup included natural ingredients such as Tulsi (*Ocimum sanctum*), Ashwagandha (*Withania somnifera*), Brahmi (*Bacopa monnieri*), Sunthi (*Zingiber officinale*), Lavang (*Eugenia caryophyllum*), honey, and water, as detailed in Table 1.

Table 1: Ingredients used in Control and Syrup

Ingredients	Control	Syrup
Tulsi	2g	2g
Ashwagandha	2g	2g
Bramhi	2g	2g
Sunthi	2g	2g
Lavang	2g	2g
Honey	100g	100g
Water	300ml	300ml
Orange peel powder	-	0.0159g
Pomegranate peel powder	-	0.0219g

Statistical Analysis

Statistical analysis was performed using GraphPad Prism 10.2.3, employing one-way ANOVA to assess significance between groups. Triplicate values for each treatment were compared to control wells, with significance levels ranging from $p < 0.05$ to $p < 0.001$. Results are presented as mean ± standard deviation, with $p < 0.05$ considered significant. Statistical significance is denoted by symbols: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, and ns (non-significant).

RESULTS AND DISCUSSION

With millions of tons of fruit waste generated annually, finding sustainable solutions for utilizing these by-products is crucial.

Proximate Analysis

The proximate analysis of orange and pomegranate peel powders reveals significant nutritional compositions, which are critical for their potential applications in pharmaceutical and nutritional industries. Table 2 summarizes the key compositional parameters of the two fruit peel powders.

The moisture content of orange peel powder was found to be 7.83%, while pomegranate peel powder exhibited a slightly higher moisture content of 8.20%. The lower moisture content in orange peels may contribute to their longer shelf life and stability, making them a more viable option for storage and processing [25]. In terms of mineral content, the ash percentage of pomegranate peel powder (7.90%) was significantly higher than that of orange peel powder (3.39%), indicating a greater mineral content in pomegranate peels and suggesting their potential as a nutrient-rich additive in food and pharmaceutical formulations [26]. The higher ash content could be attributed to a greater concentration of minerals

essential for various physiological functions in humans [27]. Additionally, the crude fiber content in pomegranate peel powder (4.12%) was higher than that of orange peel powder (2.12%), enhancing the potential of pomegranate peels as a functional food ingredient that promotes digestive health. Conversely, the fat content in orange peel powder (20.12%) was higher than in pomegranate peel powder (16.16%), with the presence of essential fatty acids in orange peel potentially adding to its therapeutic properties. Moreover, proteins were more abundant in pomegranate peel powder (18.29%) compared to orange peel powder (12.21%), enhancing the nutritional profile of pomegranate peels and making them suitable for fortification in functional food products. Lastly, carbohydrates constituted the largest proportion of the composition, with orange peel powder containing 54.23% carbohydrates and pomegranate peel powder showing a lower carbohydrate content of 45.33%. The high carbohydrate content in orange peels could be advantageous for energy provision, making them suitable for dietary applications [28].

Biochemical analysis

pH

The results showed that the pH of orange peel powder was 6.31 ± 0.24, while pomegranate peel powder had a more acidic pH of 6.67 ± 0.045 (Table 3).

Both peels exhibited slightly acidic properties, with orange peels being more acidic. These pH levels are significant as they influence the peels' potential as natural preservatives and functional ingredients in food and pharmaceutical applications. The higher acidity of orange peel powder may enhance its antimicrobial properties, making it valuable for extending the shelf life of products and reducing waste. This is particularly important given the millions of tons of fruit waste generated annually, where effective management practices can convert such by-products into beneficial resources [29]. Additionally, a study by Jalal et al. (2018) [30] reported a lower pH of 4.83 for pomegranate peel powder, pointing variations that may result from different extraction methods or cultivars.

Table 2: Proximate analysis

Sample	Moisture	Ash	Crude fiber	Fat	Proteins	Carbohydrates
Orange peel powder (%)	7.83	3.39	2.12	20.12	12.21	54.23
Pomegranate peel powder (%)	8.2	7.9	4.12	16.16	18.29	45.33

Table 3: Biochemical Analysis of Fruit peel powder

Biochemical Analysis	Orange peel powder	Pomegranate peel powder
pH	6.31 ± 0.24	6.67 ± 0.045
Bulk Density	0.4316± 0.13	0.4318± 0.019
Tapped Density	0.537 ± 0.152	0.418 ± 0.069
Hanuser Ratio	1.26 ± 0.23	0.97 ± 0.12
Compressibility Index	19.48 ± 19.64	10.12 ± 2.44

Table 4: Functional Aspects of Fruit peel powder

Functional Aspects	Orange peel powder	Pomegranate peel powder
Swelling Index/Capacity	2.88 ± 0.542	3.54 ± 0.851
Water Retention Capacity	38.96 ± 29.39	53.31 ± 10.01
Water Absorption Capacity	5.7 ± 1.51	4.67 ± 1.52
Index of Water Absorption Capacity	67.24 ± 54.59	60.77 ± 52.73
Oil Holding Capacity	16.74 ± 1.98	16.45 ± 1.64
Oil Absorption Capacity	14.22 ± 0.66	15.41 ± 0.21
Oil Retention Capacity	56.78 ± 0.001	56.92 ± 0.005
Emulsification Capacity	36.66 ± 10.92	53.10 ± 2.60
Foaming Capacity	7.72 ± 0.83	4.73 ± 0.63
Foaming Stability	1.45 ± 0.29	1.20 ± 0.20

Bulk Density and Tapped Density

The bulk density of orange peel powder was found to be 0.43 ± 0.13, slightly higher than that of pomegranate peel powder, which was measured at 0.43± 0.01 (Table 3). This suggests that orange peel powder may be more suitable for applications requiring lightweight ingredients, as noted in the study by Bader et al. [19], which highlighted its potential to increase the shelf life of gluten-free cakes due to its favorable properties. In contrast, Mall et al. [16] reported a lower bulk density of 0.27 ± 0.01 for pomegranate peel powder, indicating its efficient storage ability and reduced lipid oxidation, making it an effective option for food preservation. Tapped density results showed that orange peel powder had a

density of 0.537 ± 0.152, compared to pomegranate peel powder's 0.418 ± 0.069. This aligns with findings by Dias et al.[12], who reported a tapped density of 0.47 ± 0.01 for orange peel powder, reinforcing its potential for various food applications. The variations in bulk and tapped densities between the two peel powders suggest different functional properties that can be harnessed in food and pharmaceutical formulations. Utilizing these fruit by-products not only contributes to creating value-added products but also promotes sustainable waste management practices.

Hanuser Ratio and Compressibility Index

The Hausner ratio of orange peel powder was measured at 1.26 ± 0.23, indicating higher flowability compared to pomegranate peel powder, which had a Hausner ratio of 0.97 ± 0.12. This suggests that orange peel powder may be more suitable for applications requiring improved flow properties, such as in food processing and pharmaceutical formulations. Bader et al. (2022) [19] reported a Hausner ratio of 1.18 ± 0.0057 for orange peel powder, supporting the findings that highlight its advantageous properties. In terms of compressibility, orange peel powder exhibited a compressibility ratio of 19.48 ± 19.64, significantly higher than pomegranate peel powder's compressibility ratio of 10.12 ± 2.44 (Table 3). The higher compressibility of orange peel powder may indicate its greater capacity for volume reduction under pressure, which can be beneficial in formulation and packaging processes [31] .

Functional Attributes

The swelling index of orange peel powder was 2.88 ± 0.54, while pomegranate peel powder exhibited a higher capacity of 3.54 ± 0.851, indicating greater water-holding capacity in pomegranate peels, which enhances their potential in food formulations. Zaker et al. [14] identified orange peel as a valuable source of dietary fibers, reporting a swelling capacity of 20.74, further signifying the functional properties of peel powder in dietary applications.

The water retention capacity was also significantly higher in pomegranate peel powder (53.31 ± 10.01) compared to orange peel powder (38.96 ± 29.39). This aligns with findings from Abou-Arab et al. [15] who noted that drying methods significantly affect the functional properties of peels, with microwave drying yielding superior moisture retention. Furthermore, the water absorption capacity was recorded at 5.7 ± 1.51 for orange peel powder and 4.67 ± 1.52 for pomegranate peel powder aligning with the work of Dias et al.,[12] . This suggests that orange peel may provide better hydration properties than pomegranate peel. The index of water absorption capacity was 67.24 ± 54.59 for orange peel and 60.77 ± 52.73 for pomegranate peel, with research by Mall et al. [16] highlighting the role of water absorption capacity in regulating metabolic activity in the gastrointestinal tract.

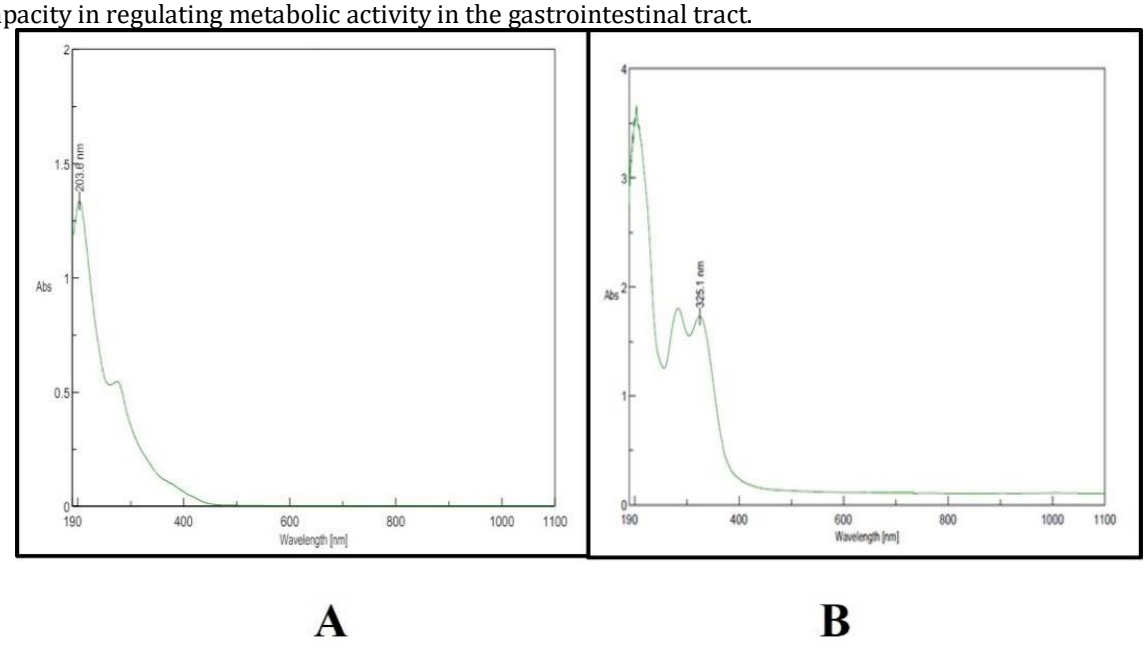


Figure 1: UV-Vis Spectra of A. Orange peel powder and B. Pomegranate peel powder

The oil holding capacity of orange peel powder was 16.74 ± 1.98, while pomegranate peel powder exhibited a slightly lower capacity of 16.45 ± 1.64. A study by Jalal et al. [30] examined the functional properties of pomegranate peel and seed, focusing on the oil holding capacity of pomegranate peel powder. This property is a physicochemical characteristic influenced by the chemical structure of plant

polysaccharides, which are affected by factors such as thickness, density, hydrophobicity, and surface properties. In terms of oil absorption capacity, orange peel powder recorded 14.22 ± 0.66 compared to 15.41 ± 0.21 for pomegranate peel powder; the latter's higher absorption capacity is relevant for its application in environmental remediation, as demonstrated by Zubaidi et al. [32], who utilized pomegranate peel powder for oil-polluted water remediation. The oil retention capacities of orange peel and pomegranate peel powders were 56.78 ± 0.001 and 56.92 ± 0.005, respectively. Furthermore, the emulsification capacity of orange peel powder was 36.66 ± 10.92, while pomegranate peel powder showed a higher emulsification capacity of 53.10 ± 2.60. The foaming capacity of orange peel powder was 7.72 ± 0.83, whereas pomegranate peel powder showed lower foaming capacity at 4.73 ± 0.63, with corresponding stabilities of 1.45 ± 0.29 and 1.20 ± 0.20, respectively. Several studies have evaluated the functional properties of orange peel powder. Bader et al.[19] reported an oil retention capacity of 2.13 ± 0.1350 g for orange peel powder. Dias et al. [12] examined the emulsification capacity and stability of apple and pineapple peel powders, finding emulsification capacities of 36.26 ± 0.20 and 41.76 ± 0.97, respectively, with both exhibiting an emulsification stability of 28.00 ± 0.00. Additionally, Bader et al. [19] also assessed the foaming capacity and stability of orange peel powder, which were found to be 8 ± 1.15 and 6.6 ± 0.88, respectively. These physicochemical properties underscore the potential of both orange and pomegranate peel powders as sustainable, functional ingredients in food and other industries, contributing to waste management by utilizing fruit by-products effectively.

Analytical Evaluation

UV-Vis Spectrophotometer

The UV-Vis absorbance spectrum of orange peel powder, as shown in Fig. 1, displayed a peak at 325.1 nm, while the pomegranate peel powder exhibited an absorbance peak at 203.6 nm. Goudanavar et al. (2018) [33] also analyzed the UV-Vis spectra of orange and pomegranate peel extracts, reporting that the absorbance for orange peel extract occurred at 280 nm and for pomegranate peel extract at 461 nm. These differences in absorbance peaks suggest variations in the phytochemical composition of the peel powders. The higher absorbance at 325.1 nm for orange peel indicates a greater concentration of certain compounds, potentially flavonoids or carotenoids, known for their antioxidant properties. Conversely, the lower absorbance at 203.6 nm for pomegranate peel may reflect the presence of phenolic compounds, which are also beneficial for health [34].

The findings support the notion that both orange and pomegranate peels are rich in bioactive compounds, which could have implications for their use in functional food formulations, natural preservatives, and waste management strategies.

FTIR

In Orange peel powder, the presence of the N-H stretching band at 3367.1 cm^{-1} indicates the presence of primary aliphatic amines, which may impart antimicrobial properties. The C-H stretching observed at 2920.66 cm^{-1} and 2850.27 cm^{-1} corresponds to alkane groups, suggesting the presence of lipophilic compounds that could enhance oil retention and absorption capacities. The C-O stretching at 2360.44 cm^{-1} is associated with carbon dioxide, while the N-O stretching at 1540.85 cm^{-1} points to organic nitrogen compounds. The O-H bending at 1417.42 cm^{-1} indicates the presence of phenolic compounds, which are known for their antioxidant properties. Additionally, the C-F stretching at 1014.37 cm^{-1} suggests the presence of fluoro compounds that may have implications in anti-scaling applications. Pomegranate peel powder exhibits a C-H stretching band at 2920.66 cm^{-1}. The C-O stretching at 2360.44 cm^{-1} indicates carbon dioxide, which is consistent with the findings in orange peel. Notably, the C≡C stretching observed at 2341.16 cm^{-1} suggests the presence of alkynes, which could contribute to the peel's bioactive properties. The S=O stretching at 1418.39 cm^{-1} indicates the presence of sulfate groups, which may be relevant in enhancing the peel's functional characteristics. Cheyad and Salman [35] studied the inhibitory activity of pomegranate peel extract on brass alloy corrosion in H_2SO_4 solutions using FTIR analysis. Their findings revealed the presence of various functional groups, including alcohols, alkenes, carboxylic acids, esters, amines, ethers, aldehydes, and ketones, with notable bonds such as O–H, C–O, C–H, and C–N. This indicates the chemical diversity of pomegranate peel, contributing to its potential antioxidant and antimicrobial properties. In a separate study, Ramakuela et al. [36] investigated the anti-scaling properties of orange peel as a water treatment agent. The FTIR spectrum of orange peel powder displayed broad absorption peaks at 3400 cm^{-1}, corresponding to O–H stretching, along with C–H stretching vibrations at 2900 cm^{-1} and 2850 cm^{-1}, highlighting its complex molecular structure. Moreover, Praipipat et al. [37] analyzed orange peel powder doped with iron (III) oxide-hydroxide, confirming the presence of functional groups such as O–H, C–H, C=C, C–O, and C=O in the FTIR spectrum. These functional groups indicate the potential for interactions between the orange peel powder and iron oxide, enhancing its applicability in environmental remediation and wastewater treatment.

Table 5: FTIR Spectrum of prepared fruit peel powder

Sample	FTIR Absorption	Frequency Range	Group	Compound
Orange peel powder	3367.1 cm^{-1}	3400-3300cm^{-1}	N-H stretched	Primary aliphatic amine
	2920.66 cm^{-1}	3000-2840cm^{-1}	C-H stretched	alkane
	2850.27cm^{-1}	3000-2840cm^{-1}	C-H stretched	alkane
	2360.44cm^{-1}	41596-1148 cm^{-1}	C-O stretched	carbon dioxide
	1540.85cm^{-1}	1550-1500cm^{-1}	N-O streched	organic nitrogen
	1417.42cm^{-1}	1420-1330cm^{-1}	O-H Bended	phenol
	1014.37cm^{-1}	1400-1000cm^{-1}	C-F stretched	fluoro compound
	2920.66 cm^{-1}	3000-2840cm^{-1}	C-H stretched	alkane
Pomegranate peel powder	2360.44 cm^{-1}	41596-1148 cm^{-1}	C-O stretched	Carbon dioxide
	2341.16 cm^{-1}	-	C≡C stretched	alkyene
	1418.39 cm^{-1}	1415-1380 cm^{-1}	S=O stretched	sulfate

Qualitative Estimation

Phytochemical analysis revealed distinct phytochemical constituents in each peel powder. Orange peel powder showed the presence of several phytochemicals, including tannins, flavonoids, coumarins, glycosides, and alkaloids. These compounds are known for their antioxidant, anti-inflammatory, and antimicrobial properties, which may contribute to various health benefits. Similarly, pomegranate peel powder contained tannins, flavonoids, coumarins, and alkaloids, indicating its potential as a source of bioactive compounds beneficial for human health [38]. As shown in Table no 6 both peel powders lacked saponins, phenols, quinones, and phlobatannins, suggesting a specific profile of phytochemicals in these extracts. Several researchers have previously reported on the phytochemical constituents of orange and pomegranate peels. El-Desoukey et al. [39] conducted a phytochemical evaluation of orange peel powder extract and identified flavonoids, alkaloids, glycosides, saponins, and tannins. Meanwhile, K. & Ganesan et al. [20] performed a comprehensive analysis of various extracts of pomegranate peel, highlighting the presence of important phytochemical constituents such as phenols, glycosides, flavonoids, terpenoids, carbohydrates, proteins, and amino acids. They concluded that these phytochemicals possess pharmaceutical properties that may enhance human health. Coumarins and alkaloids, also found in both peels, may contribute to various therapeutic activities, including antimicrobial and anticancer properties [40]. The absence of certain phytochemicals, such as saponins and phenols, in both peel powders suggests that their health-promoting properties might primarily stem from the identified compounds. The pharmaceutical properties of these phytochemicals could be further explored for their potential applications in functional foods and nutraceuticals, promoting health and wellness while also contributing to waste reduction in the food industry.

Quantitative Evaluation

Antioxidant activity evaluated through DPPH

The antioxidant activity was evaluated using the DPPH radical scavenging assay. The radical scavenging activity of 25 µg/ml of standard ascorbic acid was 95.362 ± 0.277. In comparison, orange peel powder exhibited a scavenging activity of 39.803 ± 0.170, while pomegranate peel powder demonstrated a higher activity of 54.838 ± 0.108, indicating that pomegranate peel powder possesses greater antioxidant potential than orange peel powder. Supporting these findings, Jalal et al. [30] evaluated the antioxidant activity of pomegranate peel and seed powder extracts, reporting that pomegranate peel powder showed significant radical scavenging activity ($p < 0.05$) compared to pomegranate seed powder. They concluded that both pomegranate peel and seed extracts function as free radical inhibitors, acting as primary antioxidants that react with free radicals. Further research by Sado et al. [21] assessed the antioxidant properties of citrus sinensis (sweet orange) peel and pulp oil extracts. Their findings indicated that the DPPH scavenging activity for orange peel was 14.00 ± 1.70, while the orange pulp exhibited significantly higher antioxidant activity at 85.20 ± 2.83, suggesting that the pulp has a more pronounced antioxidant effect than the peel.

The TPC of orange peel powder was found to be 0.056 ± 0.0022, while pomegranate peel powder exhibited a significantly higher TPC of 0.088 ± 0.0010. This indicates that pomegranate peel powder has a greater concentration of phenolic compounds compared to orange peel powder. Supporting these findings, Hegazy and Ibrahium (2012) [23] conducted a study on the TPC of orange peel extracts using different solvents, reporting TPC values ranging from 63.20 to 169.56 mg/g. This variability suggests that extraction methods can influence the phenolic content in orange peel. In another study, Malviya et al. [41] evaluated the TPC of pomegranate peel extracts prepared in water, ethanol, and methanol. Their results indicated that the water extract had the highest TPC, while the ethanol and methanol extracts showed comparable values without significant differences ($p < 0.05$).

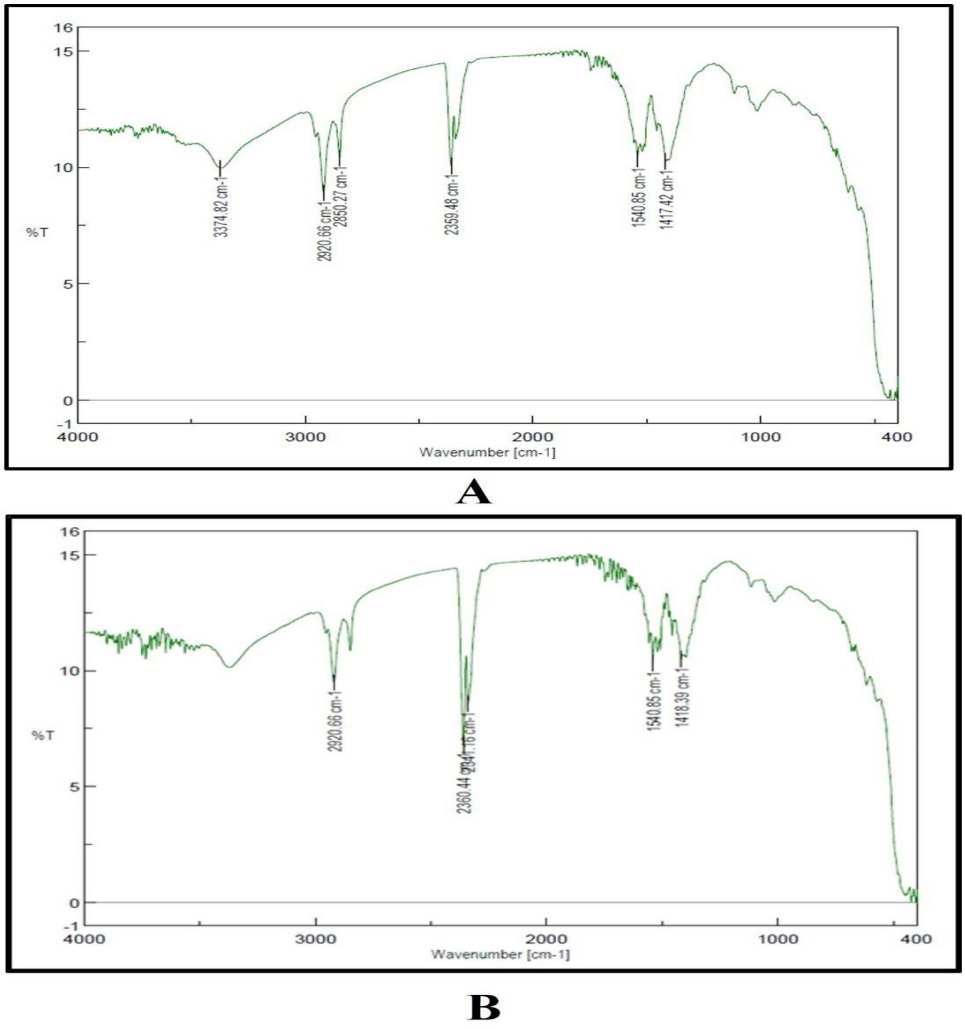


Figure 2**:** FTIR Spectra of A. Orange peel powder and B. Pomegranate peel powder

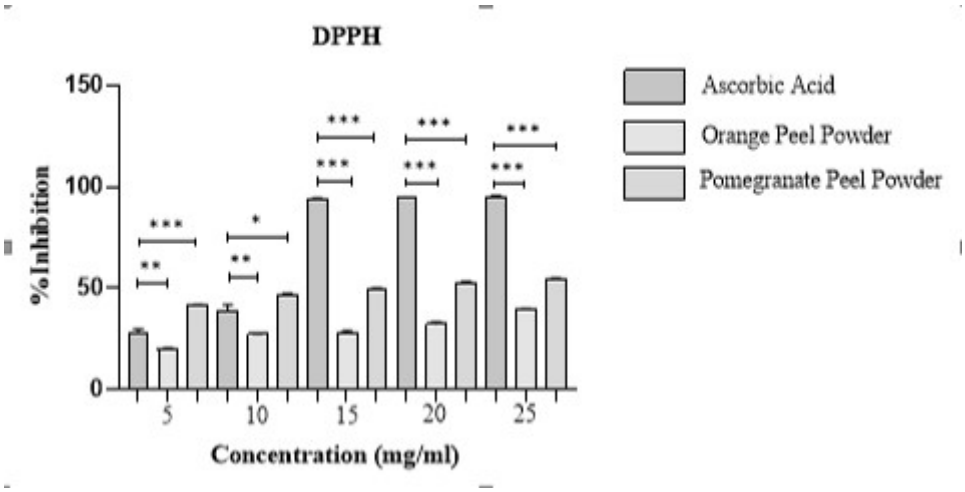
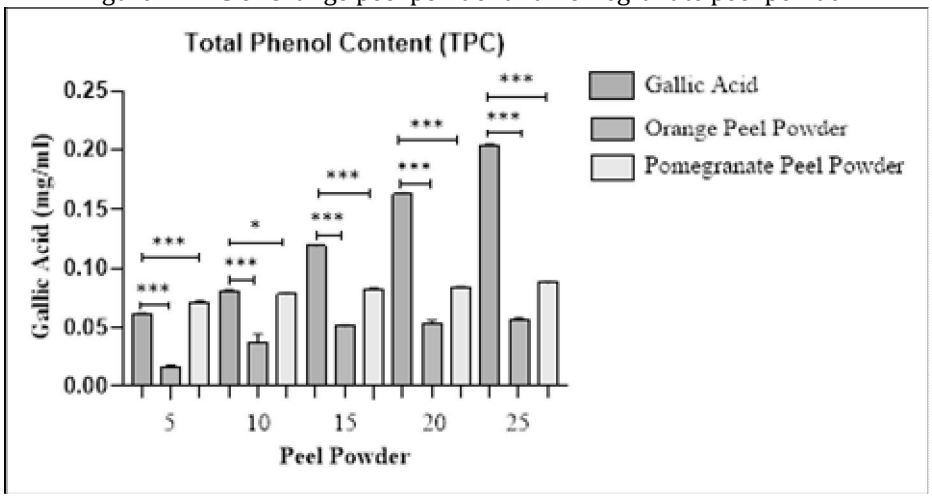


Figure 3: Antioxidant potential of the peel powders.
The data is represented as mean ± SD and significance was denoted through symbol *<0.05, **p<0.01 and ***p<0.001.

Figure 4: TPC of Orange peel powder and Pomegranate peel powder



The data is represented as mean ± SD and significance was denoted through symbol *<0.05 and ***p<0.001.

The TFC of orange peel powder was determined to be 2.79 ± 0.002, while pomegranate peel powder exhibited a TFC of 2.73 ± 0.027. These results indicate that orange peel powder has a slightly higher flavonoid content compared to pomegranate peel powder. Supporting this research, Ghasemi et al. [22] conducted a study evaluating the TFC of peels and tissues from 13 citrus species, finding that the TFC of citrus peels ranged from 0.3 to 31.1 mg quercetin equivalents, significantly higher than the standard quercetin extract range of 0.3 to 17.1 mg. The TFC values for citrus species such as *C. unshiu* var. Mahalli and *C. sinensis* var. Washington Navel were 31.1 and 23.2 mg quercetin equivalents, respectively, indicating their potential as rich sources of flavonoids. In addition, K. Ganesan et al. [20] studied the antioxidant activity of pomegranate peel powder and evaluated its TFC in various solvent extracts, including water, ethanol, acetone, and hexane. The TFC values recorded were 5.7 mg for water, 7.1 mg for acetone, 7.0 mg for ethanol, and 2.0 mg for hexane. The study concluded that the acetone extract of pomegranate peel exhibited the highest flavonoid activity among the different extracts. The presence of these phytochemicals—flavonoids and phenolics—supports the health benefits associated with citrus and pomegranate peels, which are known for their ability to scavenge free radicals and contribute to overall well-being [42].

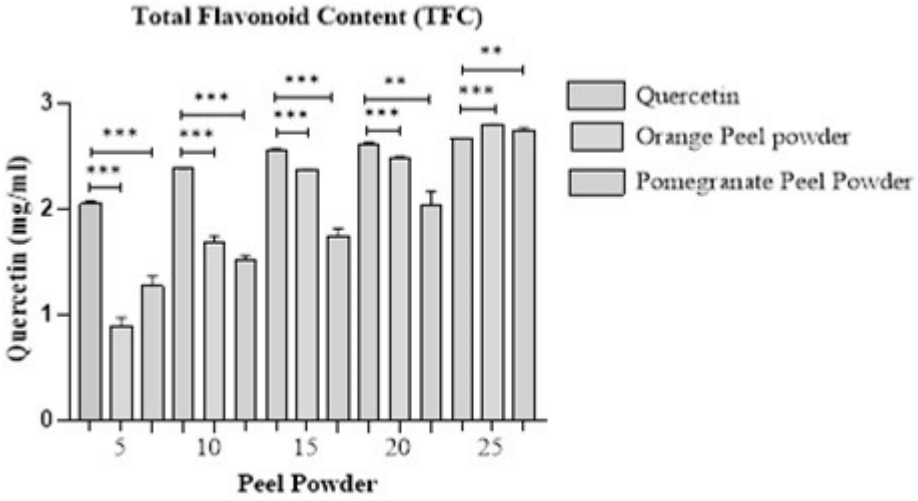


Figure 5: TFC of Orange peel powder and Pomegranate peel powder
The data is represented as mean ± SD and significance was denoted through symbol **p<0.01 and ***p<0.001.

Table 6: Phytochemical Assessment of Fruit peel powder

Phytochemical Test	Orange peel powder	Pomegranate peel powder
Tannin Test	+	+
Saponin Test	-	-
Flavonoid Test	+	+
Phenol Test	-	-
Coumarne Test	+	+
Quiones Test	-	-
Phlobatanins Test	-	-
Glycosides Test	+	-
Alkaloids Test	+	+
Steroids Test	-	-

Immunity Syrup

The incorporation of orange and pomegranate peel powders into an immunity syrup presents a promising approach to enhancing health benefits through natural ingredients. Both peel powders are identified as rich sources of bioactive compounds, including flavonoids and phenolics, which are known for their antioxidant, anti-inflammatory, and immunomodulatory properties. Flavonoids, particularly prevalent in orange peel, have been linked to improved immune function and may help combat oxidative stress, while the higher phenolic content in pomegranate peel offers additional protective effects against pathogens and chronic diseases [43].

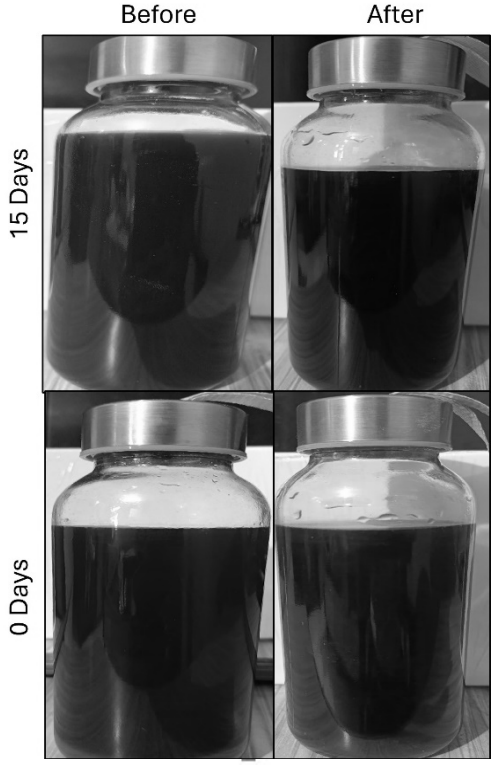
The stability of the immunity syrup was assessed by evaluating its shelf life over a period of 15 days. As depicted in fig 5, both the control and the syrup showed no visible signs of contamination or changes in viscosity, indicating that the incorporation of peel powders did not adversely affect the product's stability. This finding is crucial for ensuring that the syrup maintains its quality and efficacy over time, thus supporting its potential as a commercially viable health product. Sensory analysis was conducted to evaluate key attributes of the syrup, including color, aroma, taste, and consistency. These parameters were assessed using a hedonic scale as outlined by Lawless & Heymann (2013) [44], with ratings ranging from 1 (disliked extremely) to 5 (extremely liked). The results, presented in demonstrated that the syrup was well-received in terms of taste and aroma, which are essential for consumer acceptance. Positive sensory attributes are critical in product development, as they play a significant role in the marketability of health products. The favorable sensory profile of the immunity syrup suggests that it not only offers health benefits but also appeals to consumers' preferences.

By formulating an immunity syrup with these peel powders, their synergistic effects not only support the immune system but also promotes overall health. This syrup can serve as a convenient and effective way to incorporate the nutritional benefits of these peels into daily routines, making it accessible for consumers seeking natural solutions to enhance their immunity. Furthermore, the syrup can cater to health-conscious individuals looking for functional foods that provide holistic wellness benefits, emphasizing the importance of using natural sources to support health and vitality.

Expanding on future prospects, there is significant potential to explore other fruit wastes with health benefits and valuable bioactive components. Research into a wider variety of fruit by-products could uncover unique compounds for immune support, preventive health, and even treatments for rare diseases. Additionally, developing pharmaceutical and nutraceutical products using these bioactive ingredients could lead to innovative, sustainable solutions in healthcare, furthering both environmental stewardship and public health.

The incorporation of orange and pomegranate peel powders into an immunity syrup exemplifies a proactive approach to waste management. By transforming waste into valuable products, this initiative not only minimizes environmental impact but also highlights the potential health benefits associated with these by-products. However, to fully realize such benefits, organizations must address challenges like limited awareness and resistance to change. Comprehensive sustainability strategies that involve stakeholder engagement, employee training, and innovative processing techniques are crucial. Leadership plays a pivotal role in this transformation by inspiring a culture of innovation and prioritizing sustainability as a core value. By fostering communication and collaboration, companies can navigate the complexities of sustainable practices, enhancing both environmental performance and consumer well-being, while paving the way for a more sustainable future in the food industry and beyond.

Figure 6: Before and After Shelf Life of Control and Syrup



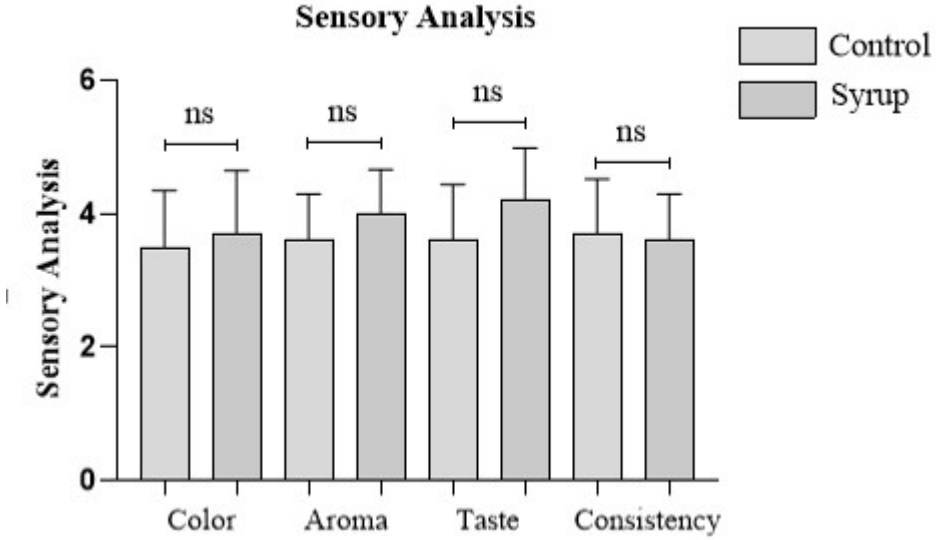


Figure7: Sensory Evaluation of Control and Syrup
The data is represented as mean ± SD and significance was denoted through symbol ns.

CONCLUSION

In conclusion, this study effectively demonstrates the fortification of phytochemicals and antioxidants from orange and pomegranate peel waste into a natural immunity syrup. By utilizing fruit waste, which contains valuable bioactive compounds such as phenols, flavonoids, and vitamins, the research highlights the potential of these peels to promote immune function and support overall health. Comprehensive biochemical analysis confirmed the rich presence of these beneficial compounds, extending their medicinal properties. The resulting immunity syrup not only showcases the effective use of fruit waste but also contributes to sustainable practices in the food industry. This work emphasizes the importance of natural ingredients in enhancing human health and supports further exploration of fruit waste valorization for public health benefits. Moreover, this approach serves as a model for effective waste

management and sustainability, showcasing how the transformation of agricultural by-products into functional health products can minimize environmental impact while maximizing resource efficiency.

Conflict of Interest Statement

Author declares no conflict of interest.

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