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RESEARCH ARTICLE

Ultrasound-assisted extraction of antioxidants from watermelon rind using green solvent for food and cosmetic applications

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ABSTRACT

Watermelon *(Citrullus lanatus)* rind often discarded as agricultural waste, contains valuable bioactive compounds such as citrulline, phenolics and flavonoids. This study investigates the impact of solvent polarity on the efficiency and phytochemical profile of watermelon rind extracts using ultrasound-assisted extraction (UAE). Extractions were performed with ethanol, ethyl acetate, and hexane under fixed conditions (30°C, 70 minutes, 1:10 solid-to-liquid ratio). Extracts were analyzed for total phenolic content (TPC), total flavonoid content (TFC), and antioxidant activity using the DPPH radical scavenging assay. Ethanol yielded the highest TPC (4.47 ± 0.03 mg GAE/g) and antioxidant activity (IC_{50}: 4.56 µg/mL), while ethyl acetate exhibited the highest TFC (1.292 ± 0.02 mg QE/g) with comparable antioxidant potential. The results demonstrate that solvent polarity significantly affects the recovery of bioactive compounds, with ethanol and ethyl acetate efficiently extracting hydrophilic and moderately lipophilic constituents. By demonstrating that watermelon rind may deliver high antioxidant recovery utilizing UAE, this study demonstrates its potential as a value-added source rather than a waste product. When combined with UAE, ethanol excels out as a safe and practical green solvent, presenting a scalable and environmentally responsible approach to develop watermelon rind into useful ingredients for food, nutraceutical, and cosmetic applications.

1. INTRODUCTION

Interest in valuing agricultural waste products, particularly those high in bioactive compounds, has greatly increased as a result of the growing emphasis on sustainable development and the concepts of the circular economy. The need to use all available resources and reduce waste has grown increasingly important as the world's population continues to increase. Peels, rinds, and seeds make up a sizable amount of the solid waste from fruits and vegetables that is still not being used. In addition to being a significant environmental problem, this underutilization is a lost chance to collect essential phytochemicals that could help a number of industries, including the food and cosmetics sectors (Ghaedrahmati et al., 2021). As a result, As a result, agro-industrial waste—which includes leftovers from the processing of fruits and vegetables—is becoming more and more recognized as a sustainable source of substances with anti-inflammatory, antibacterial, and antioxidant qualities. This insight is driving industries to implement eco-friendly, waste-reducing practices that comply with international sustainability standards and goals (Bala et al., 2023; Ngwasiri et al., 2022).

Among the most extensively consumed fruits worldwide, watermelon *(Citrullus lanatus),* produces a lot of rind waste, which makes up around 35% of the fruit's mass (Ahamad et al., 2022). This rind, which is frequently thrown away as a byproduct, holds promise as a source of useful molecules. These consist of citrulline, phenolic acids, cellulose, hemicellulose, lignin, pectin, lycopene, flavonoids, and phenol. Despite their documented antioxidant, anti-inflammatory and physiological functions, these bioactive compounds are frequently discarded during commercial processing. This practice represents a significant loss, as these compounds hold immense untapped potential for various applications in food and cosmetics, where their functional properties could be of great value (Gu et al., 2023; Nadeem et al., 2022).

To recover these bioactive constituents effectively, suitable extraction methods are crucial. Traditional methods such as Soxhlet extraction, maceration and hydro-distillation have been widely used, but these techniques are often time-

consuming, solvent-intensive and prone to the thermal degradation of heat-sensitive compounds (Taofiq et al., 2019). In this regard, ultrasound-assisted extraction (UAE) has emerged as a particularly promising environmentally friendly and efficient option. Reduced extraction time, lower energy and solvent use, increased yield, and improved preservation of thermo-labile compounds are just a few of the many benefits that UAE offers over traditional approaches (Mansur et al., 2019; Senrayan & Venkatachalam, 2019). This mechanism functions by causing tiny bubbles in the solution to develop and breakdown. Their detonation results in localized heat and tension which enhance the cell wall collapse and solvent penetration. This mechanism significantly fasten mass transfer and facilitates the release of phenolic, flavonoids and other bioactive constituents comparable to conventional methods (Shen et al., 2023).

The potency of UAE has been thoroughly shown in a variety of plant matrices. For instance, it has been shown that UAE of orange peel with ethanol has greater antioxidant activity than traditional approaches (Hishamuddin & Razali, 2025; Shen et al., 2023). Grape and pomegranate peels treate to UAE using green solvents such as ethanol and ethyl acetate also demonstrated considerably enhanced total phenolic content (TPC) and improved antioxidant capacity (González et al., 2020; Sejuk, 2021; Siddiqui et al., 2024). The efficiency of this method in extracting bioactive constituents from agricultural waste is further supported by recent research employing UAE on watermelon peel revealed notable increase in TPC and antioxidant potential (Vo et al., 2022; Zia et al., 2024).

One important factor that influences bioactive recovery in UAE is solvent polarity. Phenolic compounds are best extracted by polar solvents like ethanol, while flavonoids are suitable to be extracted by semi-polar solvents such as ethyl acetate. For antioxidant, non-polar solvents like hexane perform weakly as they are less soluble towards polar compound (Puspito et al., 2024). Importantly, ethanol and ethyl acetate are both considered as green solvents due to their biodegradability, low toxicity, and regulatory acceptability which qualifies them for environmentally benign uses in various industries. Despite the promising phytochemical profile of watermelon rind, most prior studies have either employed conventional extraction methods or single-solvent systems and have not comprehensively examined the combined influence of solvent polarity and UAE conditions. This gap limits current understanding of how to optimize the extraction process for specific classes of bioactive compounds (Zia et al., 2024).

The bioactive-rich extracts obtained through UAE with appropriate green solvent offer significant industrial potential. In food systems, natural antioxidants from plant-based sources can extend product shelf life, reduce reliance on synthetic additives and improve nutritional profiles (Ali et al., 2025; Vlaicu & Untea, 2024). In cosmetics, these extracts have anti-aging, photoprotective, and skin-calming qualities that meet consumer desire for plant-derived, clean-label constituents (Lakshmikanthan et al., 2024; Michalak, 2023). As consumer tastes continue to move toward natural ingredients and sustainability, the UAE's watermelon rind value-adding initiative offers a timely chance to cut down on agricultural waste and produce high-value useful chemicals.

Therefore, the objective of this study is to explore the effect of solvent polarity on the extraction of total phenolic content (TPC), total flavonoid content (TFC), and antioxidant activity from watermelon rind using UAE. This study enhances sustainable extraction technologies by determining the most effective solvent system and encourages the conversion of agricultural waste into functional components for the food, nutraceutical, and cosmetic industries.

2. MATERIALS AND METHODS

2.1. Materials

Solvents used for extraction were analytical grades including ethanol (2.5 L, purity ≥ 99.9 %, HMBG), hexane and ethyl acetate (2.5 L, purity ≥ 95 %, Merck). Chemicals and reagents used for phytochemical analysis were analytical grade including sodium carbonate and aluminium chloride (500 g, purity ≥ 99 %, Bendosen), 2,2-diphenyl-1-picrylhydrzyl (DPPH) reagent (250 mg, purity ≥ 95 %, Alfa Aesar), Folin–Ciocalteu reagent (500 mL, purity ≥ 98 %, R&M), gallic acid and quercetin (20 mg, purity ≥ 98 %, Sigma-Aldrich), ascorbic acid (100 g, purity ≥ 99 %, HMBG) and distilled water (laboratory grade).

2.2 Sample collection and preparation

Two medium-sized, fully ripened Crimson Sweet watermelons (*Citrullus lanatus*), each weighing approximately 4 kg were purchased from a local market in Jeli, Kelantan. The watermelons exhibited an oval shape with dark green stripes on the rind, while the flesh was red with few seeds. After thorough washing, the red pulp and outer green skin were removed using a peeler and the remaining rind was cut into uniform slices measuring approximately 40 × 20 mm. The rind pieces were then dehydrated in a food dehydrator (Autumnz , 245 W, 5 kg) at 60°C for 36 hours, following conditions optimized by Lim et al. (2020), to effectively reduce the high moisture content (~90 %). Once dried, the rinds were crushed into a fine powder, sieved using a 25-mesh screen and stored at room temperature in airtight containers for further analysis.

2.3. Extraction of watermelon rind

Ultrasound-assisted extraction (UAE) was employed using an ultrasonic bath (RS PRO Ultrasonic Cleaner, 100 W, 3 L) operating at a frequency of 40 kHz and an intensity of 5.5 W/cm². Referring to Vo et al. (2022) with some modifications, a fixed extraction condition was applied for all the solvents: temperature of 30°C for 70 minutes, and a solid-to-liquid ratio of 1:10 (w/v). For each extraction, 1 g of prepared watermelon rind powder was mixed with 10 mL of solvent (100% ethanol, ethyl acetate or hexane). After sonication, the mixtures were filtered through Whatman No. 1 filter paper. The filtrates were then concentrated under reduced pressure at 40°C using rotary evaporator, and the extracts were stored at 4°C until further analysis.

2.4. Antioxidant Assay

The antioxidant capacity of watermelon rind extracts was evaluated using the DPPH radical scavenging activity, with some modifications to the protocols given by Phuyal et al. (2020). A 0.1 mM DPPH solution was prepared in ethanol and 1400 µL was combined with 100 µL of watermelon rind extract at different concentrations (1.56 - 100 µg/mL). The sample was incubated in the dark at room temperature for 30 minutes to hasten the process. After incubation, the absorbance was measured at 517 nm using a UV-Vis spectrophotometer (Shimadzu UV-1900), with blank (ethanol) and control (DPPH solution in ethanol). Ascorbic acid at varying concentrations (1.56 - 100 µg/mL) was used as a standard control for its water-soluble antioxidant properties that makes it appropriate for hydrophilic plant extracts like watermelon rind. The percentage of radical scavenging activity (RSA) was calculated using the following equation:

$$Radical\ Scavenging\ Activity\ (\%) = \frac{A_0 - A_1}{A_0} x\ 100$$

Where, A_0 is the absorbance of the control and A_1 is the absorbance of the sample or standard. The IC_{50} values (concentration required to block 50% of DPPH radicals) were computed using linear regression analysis and applied to analyze the antioxidant capacity of the extracts in comparison to standard.

2.5. Total Phenolic Content (TPC)

The Folin-Ciocalteu (FC) technique was employed to quantify the total phenolic content (TPC) of watermelon rind extracts, following the procedure described by Phuyal et al. (2020). After mixing 100 µL of extract with 150 µL of FC reagent, the mixture was incubated for five minutes in the dark and then added 500 µL of a 7.5% sodium carbonate (Na_2CO_3) solution to be incubated for an additional half hour. A UV-Vis spectrophotometer (Shimadzu, UV-1900, 29 000 nm/min) was used to measure the absorbance at 765 nm and in triplicates. Gallic acid functioned as standard at varying quantities (50–500 µg/ml) by following the same procedure. The TPC of watermelon rind extracts was determined using the following equation and represented as gallic acid equivalent (mg GAE/g) based on the calibration curve.

$$Total\ Phenolic\ Content\ \left(mg\frac{GAE}{g}\right) = x\ \left(\frac{v}{m}\right)$$

Where, *x* is the concentration of gallic acid obtained from the calibration curve (µg/ml), *v* is the volume of extraction solvent (µL) and *m* is the mass of the extract (g).

2.6. Total Flavonoid Content (TFC)

Based on Phuyal et al. (2020), the total flavonoid content in the watermelon rind extracts were evaluated using 10% aluminium chloride ($AlCl_3$) colorimetric technique. A 100 µL of extract, 100 µL of 10% $AlCl_3$ were mixed into 100 µL of 1M of potassium acetate and was allowed to set in dark at room temperature for 45 minutes. Following the same procedure, standard solution was prepared in different concentrations (50-500 µg/ml) using quercetin. A blank was prepared using methanol in $AlCl_3$ and potassium acetate only. The absorbance of the reaction was measured at 510 nm in triplicate by using UV-Vis spectrophotometer (Shimadzu, UV-1900, 29 000 nm/min). From the calibration curve, the total flavonoid content was calculated using equation below and expressed as quercetin equivalent (mg QE/g).

$$Total\ Flavonoid\ Content\ \left(mg\frac{QE}{g}\right) = x\ \left(\frac{v}{m}\right)$$

Where, *x* is the concentration of quercetin obtained from the calibration curve (µg/mL), *v* is the volume of extraction solvent (µL) and *m* is the mass of the extract (g).

3. RESULT AND DISCUSSION

3.1 Antioxidant Activity

The antioxidant potential of watermelon rind extracts was evaluated using the DPPH radical scavenging assay, with ascorbic acid as the standard reference. The assay is widely used due to its simplicity and ability to measure the capacity of antioxidants to donate electrons and neutralize free radicals. The radical scavenging activity (RSA) of watermelon rind extracts ranged between 24.57% and 53.79% (Figure 2). In comparison, ascorbic acid had the greatest ranges RSA range of 25.21% to 91.41% (Figure 1). These findings demonstrate that although watermelon rind extracts have achieved acceptable level of antioxidant capacity, they are not as effective as the well-known high and powerful antioxidant like ascorbic acid.

Among the solvents examined, the ethanol extract had the highest RSA values (30.87% to 53.79%), followed by the ethyl acetate extract (24.57% to 41.31%) and the hexane extract (26.73% to 36.86%). The enhanced RSA of the ethanol extract may be attributed to its capability to extract variety of bioactive constituents, including phenolic compounds, which are known antioxidants. These findings are consistent with prior studies by demonstrating ethanol had higher antioxidant capacity on watermelon peels. Using maceration technique, Wakid & Harun (2020) discovered that RSA values in ethanol extracted plant materials could range from 50.1 to 96% (IC_{50}: 4.93 µg/mL). Similarly, the effectiveness of ethanol during antioxidant extraction suggested by Ho et al. (2018), who employed infusion technique and discovered that ethanol extracts had a higher RSA (73.19%) than water extracts (54.70%).

The antioxidant properties of extracts were further explained by the IC_{50} values. As illustrated in Figure 3, ascorbic acid had the highest antioxidant capacity with the lowest IC_{50} value of 3.28 µg/mL. Meanwhile, ethanol extract of watermelon rind achieved second highest IC_{50} of 4.56 µg/mL, indicating similar antioxidant activity to satndard. The hexane and ethyl acetate extracts, on the other hand, had lesser antioxidant capability with higher IC_{50} values of 10.40 µg/mL and 7.19 µg/mL, respectively. These findings align with the RSA data, where the ethanol extract demonstrated the strongest radical scavenging activity. A lower IC_{50} value indicates a more potent antioxidant, and the comparable IC_{50} of the ethanol extract to ascorbic acid further highlights ethanol's efficiency in extracting antioxidants from watermelon rind.

Moreover, extraction methodology significantly impacted antioxidant yield. Ultrasound-assisted extraction (UAE) proved to be a highly effective green technology, as the cavitation effect enhances cell wall disruption and mass transfer, leading to greater release of bound phenolic. Optimization studies of watermelon rind under UAE reported a maximum DPPH value of 2.96 ± 0.03 µM Trolox/g db and ABTS value of 55.18 ± 1.16 µM Trolox/g db at optimized conditions using 70% acetone for 30 minutes (Vo et al., 2022). Similar study by Zia et al. (2024) using acetone for UAE have also revealed that 80% acetone with 20 min sonication achieved the highest antioxidant activity, whereas excessively high solvent concentrations (e.g., 95%) reduced DPPH values. This indicates that UAE not only improves extraction efficiency but also requires careful adjustment of process parameters to prevent compound degradation or reduced bioactivity. This indicates that UAE not only improves extraction efficiency but also requires careful adjustment of process parameters to prevent compound degradation or reduced bioactivity.

Overall, the results demonstrate that solvent polarity, and extraction methodology collectively influence the antioxidant potential of watermelon rind. Ethanol consistently emerged as the most effective solvent, offering high RSA and low IC_{50} values, while UAE further enhanced antioxidant recovery under optimized conditions. Given ethanol's amphiphilic nature, low toxicity and regulatory acceptance, ethanol-based UAE provides a green, scalable, and industrially relevant strategy to maximize the antioxidant value of watermelon rind for applications in food, nutraceutical, and cosmeceutical industries.

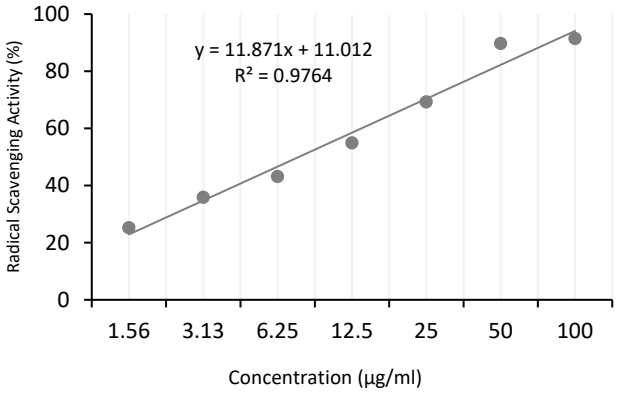

Figure 1: The radical scavenging activity (RSA) of standard (ascorbic acid).

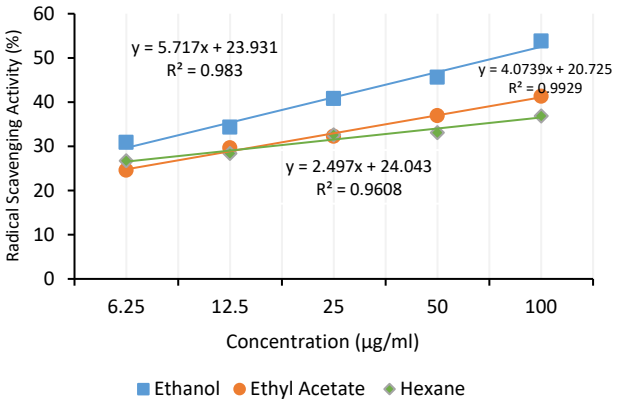

Figure 2: The radical scavenging activity (RSA) of watermelon rind extracts.

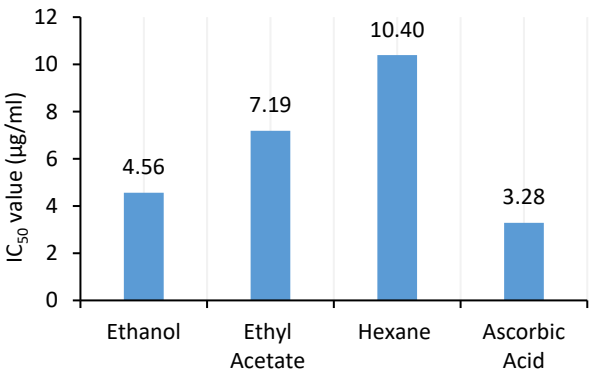

Figure 3: Comparison graph of the 50% inhibition concentration (IC_{50}) between the standard (ascorbic acid) and the watermelon rind extracts.

3.2 Total Phenolic Content (TPC)

The total phenolic content (TPC) of watermelon rind extracts was quantified using the Folin-Ciocalteu method, a widely accepted assay for measuring phenolic compounds due to its sensitivity and ease of use. A calibration curve (Figure 4) was constructed using gallic acid as the standard, yielding a linear regression equation of y = 0.1165x + 0.1972, with a coefficient of determination (R^2 = 0.9913), indicating strong linearity and a reliable calibration model for quantification.

As shown in Figure 5, the ethanol extract exhibited the highest TPC (4.474 ± 0.03 mg GAE/g), followed by the ethyl acetate extract (0.915 ± 0.05 mg GAE/g) and the hexane extract (0.463 ± 0.07 mg GAE/g) of watermelon rind. These results highlight the significant influence of solvent polarity on the extraction efficiency of phenolic compounds. The ethanol extract, being a polar solvent demonstrated the highest TPC which influenced by its ability to solvate and extract polar phenolic compounds more effectively than the less polar ethyl acetate and hexane solvents.

While the results of this study demonstrate a relatively lower TPC values compared to some reports in the literature, for example Kamal et al. (2023), reported values range from 56.975 to 88.245 mg GAE/g using maceration extraction, the overall trend of ethanol outperforming other solvents remained consistent. Similarly, Ho et al. (2018) found that ethanol extracts of Crimson Sweet watermelon rind achieved a TPC of 195.81 ± 0.47 mg GAE/100 g, surpassing methanol (183.96 ± 0.25 mg GAE/100 g) during infusion. These discrepancies in reported TPC values can be attributed to differences in experimental conditions such as extraction temperature, duration, solvent concentration, and the specific cultivar of watermelon rind.

When compared with optimized ultrasound-assisted extraction (UAE) studies, higher TPC values have been reported. For instance, Vo et al. (2022) obtained a maximum TPC of 6.21 ± 0.24 mg GAE/g db (dry basis) under optimized UAE conditions of 70% acetone at 30 °C for 10 minutes. This indicates that, in comparison to non-optimized extraction, UAE greatly improves phenolic recovery because of acoustic cavitation, which breaks down plant cell walls and enhances mass transfer. However, chemical breakdown and lower solubility caused phenolic yields to fall beyond the ideal solvent concentration (e.g., 90–95% acetone).

The increased efficacy of ethanol in extracting phenolics from watermelon skin can be due to its polarity and capacity to establish hydrogen bonds with the hydroxyl groups prevalent in phenolic compounds. This interaction promotes solubilization and increases phenolic chemical release during UAE (Huamán-Castilla et al., 2024). Ethanol's propensity to damage plant cell structures and interact with hydrophilic chemicals makes it very successful for recovering bioactive phenolic acids like ferulic acid, syringic acid, and oleuropein (Thavamoney et al., 2018).

Considered collectively, our findings support the importance of solvent polarity and extraction process in affecting phenolic yield. Ethanol consistently shown to be the most effective solvent for phenolic extraction, whereas UAE improved phenolic recovery under optimal conditions. Although the TPC values reported here were lower than those of other conventional extractions, the observed trends significantly support ethanol-based UAE as a green, efficient, and scalable method for extracting phenolics from watermelon rind.

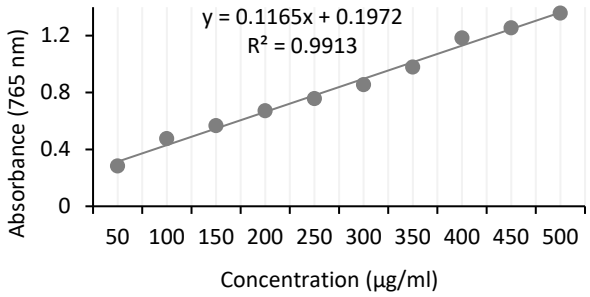

Figure 4: Calibration curve of gallic acid.

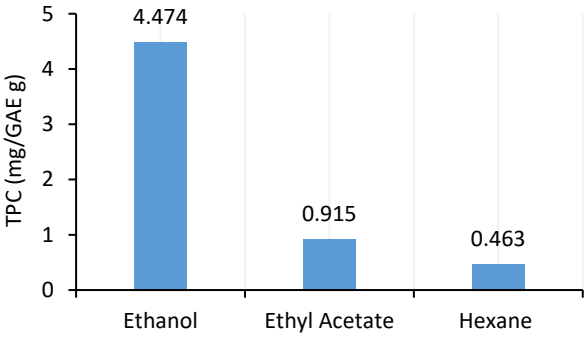

Figure 5: Comparison graph of Total Phenolic Content (TPC) among watermelon rind extracts.

3.3 Total Flavonoid Content (TFC)

The aluminum chloride colorimetric method, which is a dependable methodology for quantifying flavonoids due to its sensitivity and specificity for these chemicals, was used to measure the total flavonoid content (TFC) of watermelon rind extracts. A calibration curve (Figure 6) was constructed using quercetin as the reference standard, yielding a linear regression equation of y = 0.1542x + 0.0011, with a strong linear correlation (R^2 = 0.9892). This high R^2 value indicates that the calibration curve was well-defined and the method provided accurate and reproducible measurements for flavonoid content.

As demonstrated in Figure 5, the ethyl acetate extract exhibited the highest TFC (1.292 ± 0.02 mg QE/g), followed by the ethanol extract (1.104 ± 0.02 mg QE/g) and the hexane extract (0.497 ± 0.02 mg QE/g). These findings explains the important function of solvent polarity during extraction and solvability of flavonoid molecules. The semi-polar solvent like, ethyl acetate shown effective specifically for retrieving flavonoids. This is probably due to its intermediate polarity, which allows it to extract a variety of flavonoids that have both hydrophilic and lipophilic characteristics. The effectiveness of solvent is imputed to its capacity to engage between hydrogen bonding interactions of flavonoid, which promotes the release of these bioactive substances from plant cell walls.

These results are in line with prior research flavonoids extraction from watermelon rind. For instance, a TFC of 1.85 ± 0.54 mg QE/g was reported for ethanol extracted Crimson sweet watermelon peel (Hishamuddin & Razali, 2025) which confirms the flavonoid extrability discovered in this study. In a similar vein, Ho et al. (2018) reported that red watermelon rind cultivar was better extracted by water (13.95 to 193.43 mg CEQ/100g) than aqueous ethanol extract. This efficiency of flavonoid extraction by both solvent polarity and phytochemical profile could be reflected by given cultivar. Moreover, different watermelon cultivars may produce varying amounts and types of flavonoids, according to their genetic variances that lead to shifts in flavonoid content.

Several fruit matrices have also been shown to exhibit comparable solvent-dependent patterns. Employing sequential extraction for *Dacryodes rostrata,* shown ethyl acetate extract with highest yield (9289.8 mg QE/100g), followed by ethanol extract (8189.0 mg QE/100g) and hexane extract (177.2 mg QE/100g) (Thavamoney et al., 2018). Since ethyl acetate continuously outperformed other solvents in terms of TFC, as was the case with watermelon rind extracts, this study further supports the importance of solvent polarity in effective flavonoid extraction.

When compared with optimized UAE studies higher TFC values have been reported. For instance, Vo et al. (2022) obtained a maximum TFC of 3.51 ± 0.18 mg rutin/g db (dry basis) at optimized UAE conditions of 70 % acetone at 30 °C, for 10 minutes. This demonstrates the ability of UAE to significantly enhance flavonoid recovery compared to non-optimized extractions. However, extraction beyond optimal sonication time (>10 min) or using excessively high solvent concentrations led to degradation of flavonoids, thereby reducing yields. This indicates that UAE efficiency is strongly dependent on fine-tuned process parameters.

Ethyl acetate may offer a slight advantage in terms of high flavonoid yield recovery, however ethanol remains a highly effective and practical alternative due to its amphiphilic properties, which allow it to dissolve both hydrophilic and lipophilic compounds. Chaves et al. (2020) assert that because ethanol is less hazardous, biodegradable and typically allowed by regulatory frameworks as it is safer and more sustainable substitute for industrial scale extraction procedure. This is particularly crucial for value-adding of agricultural wastes like watermelon rind, to comply industrial and environmental standards during the extraction process by ensuring safety and sustainability.

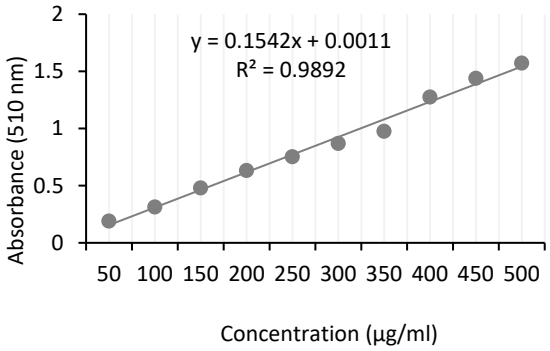

Figure 6: Calibration curve of quercetin.

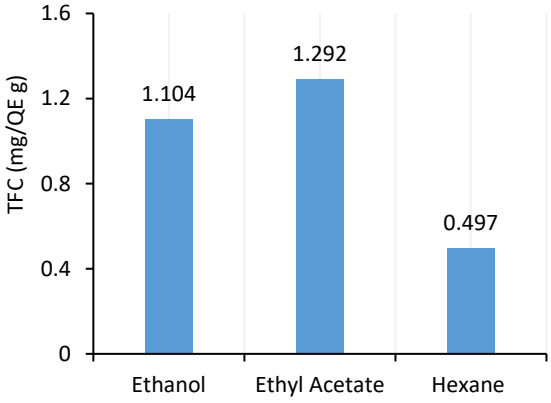

Figure 7: Comparison graph of Total Flavonoid Content (TFC) among watermelon rind extracts.

4. CONCLUSION

The significance of solvent selection was brought to light in this study by the application of ultrasound-assisted extraction (UAE) to enhance the phytochemicals recovery in watermelon rind extracts. According to the findings, ethanol was the greatest solvent for withdrawing bioactive compounds and boosting their overall antioxidant capacity, meanwhile ethyl acetate was particularly effective at recovering flavonoids. Although the absolute phytochemical contents achieved were lower than in some previous studies, the UAE technique along with importance of solvent selection during extraction were highlighted, as the patterns were consistent

with established findings.

Interestingly, both ethyl acetate and ethanol are classified as green solvents. The amphiphilic characteristic of ethanol makes it safe, biodegradable, and appropriate for use in food and cosmetic applications while dissolving a variety of phenolic compounds. Since ethyl acetate is biodegradable and comparatively non-toxic, it is particularly useful for extracting flavonoids and other moderately polar chemicals due to its intermediate polarity. These solvents' use highlights how crucial it is to implement efficient, environmentally friendly extraction techniques that follow the rules of green chemistry.

This work adds to the expanding body of evidence supporting green extraction technologies and underscores the untapped potential of watermelon rind as a valuable source of bioactive compounds. By converting agricultural waste into valuable active ingredients, this approach not only supports sustainability objectives but also opens up promising opportunities for the development of a wide range of consumer goods.

Looking forward, further optimization of UAE parameters and chromatographic profiling of individual compounds will deepen our understanding of the specific phytochemicals responsible for antioxidant activity. *In-silico* studies (e.g., molecular docking and computational modeling) could complement these findings by predicting interactions between watermelon rind phytochemicals and biological targets, shedding light on potential antioxidant, anti-inflammatory, or therapeutic mechanisms. Additionally, *in-vivo* studies and stability testing are vital to validate the functional and therapeutic potential of these extracts, ensuring their safe and effective use in commercial applications. These steps will help bridge the gap between laboratory findings and real-world applications, advancing the valorization of watermelon rind as a bioactive resource across various industrial sectors, including food, nutraceuticals, and pharmaceuticals.

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