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Augmenting pomelo juice quality through membrane-based clarification and bioactive compounds recovery

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ABSTRACT

The presence of impurities, microorganisms, enzymes, suspended solids, and impurities in unclarified pomelo juice negatively affected the quality and shelf-life of the product in the food industry. The objective of this study focuses on the clarification of fresh pomelo juice using an ultrafiltration (UF) process. The study examined the influence of the operating pressure (OP) on the various quality attributes of pomelo juice, such as pH, total soluble solids (TSS), turbidity, color, total phenolic content (TPC), ascorbic acid content (AAC) and fouling mechanisms and permeate flux (J) behavior. To perform the clarification of pomelo juice, a 100 kDa membrane (polymeric) was used in a dead-end system, and the process was carried out in batch mode at OP values of 1.0, 1.5, 2.0, 2.5 and 3.0 bar. The findings revealed that increasing OP led to higher flux during ultrafiltration with limiting pressure (P_{lim}). The limiting pressure (P_{lim}) was anticipated to be beyond 3.0 bar due to the enzymatic pretreatment. The primary fouling mechanism during the clarification process was total pore blocking. After filtration, the resulting juice showed a significant reduction in turbidity of over 97%, while TSS was lowered by 7–17% compared to fresh juice. The pomelo juice was efficiently clarified while the pH remained stable at ~3.8. The clarified juice showed a minor decline of 10.1–13.9% in TPC and a 10.8–16.7% reduction in AAC compared to the fresh unclarified juice. In conclusion, a pressure of 3.0 bar is recommended for conducting the ultrafiltration process in order to attain desirable flux behavior and optimum properties of the juice.

KEYWORDS

Pomelo juice; clarification; membrane process; ultrafiltration; flux

Introduction

Pomelo, scientifically known as *Citrus maxima* or *Citrus grandis*, is a sizeable citrus fruit that originates from Southeast Asia. Pomelo juice is a nutritious and refreshing beverage that is rapidly gaining acceptance around the world. It has been traditionally used for medicinal and culinary benefits and has recently been recognized as a valuable source of healthy juice production (Nguyen et al. 2022). Pomelo juice offers several important health advantages due to its abundance of vital minerals as well as vitamins, such as vitamin A, vitamin C, B5, B3, B2, and B5, as well as calcium, potassium, and magnesium (Davarci et al. 2019).

These nutrients are highly essential in neutralizing harmful free radicals in the body and protecting against cellular damage. They also play a crucial role in sustaining a healthy immune system and preventing or treating conditions such as the common cold, flu, and various body infections (Dal Magro et al. 2019). Besides, several studies have reported that pomelo has anti-cancer properties and may contribute to protection against the development of certain types of cancer, lower cholesterol levels, improve insulin sensitivity, and reduce inflammation in the body (Zeng et al. 2022).

However, similar to other conventional fruit juices, pomelo juice contains large molecules

such as polysaccharides, including cellulose and hemicellulose, and pectin that could undermine the properties of the juice if stored for prolonged durations than a short period for commercial purposes (Kharazmi et al. 2020). These colloids trigger the cloudiness, turbidity, and viscosity of fruit juice, which decreases consumer recognition in certain markets, either as untreated pomelo juice or as blends with various juices. These macromolecules can be removed through many clarification techniques, such as centrifugation and flocculation. However, these techniques presented several drawbacks, including the presence of residual chemicals in the juice, high energy consumption, expensive, unpredictable results, the heat produced during centrifugation can cause degradation of the juice quality, time-demanding, process feasibility, and the use of chemical agents (Yousefnezhad et al. 2017; Gulec et al. 2018; Omar et al. 2020).

Interestingly, the membrane filtration process presented an outstanding alternative for the juice clarification, as it eliminates the need for chemical agents or phase transition, operates efficiently under mild conditions, is relatively inexpensive, and can be easily scaled up (Katibi et al. 2021; Yee et al. 2021). The categorization of membrane processes is based on the force driving the filtration and the size of the pores. These categories encompass several techniques, such as nanofiltration, microfiltration, ultrafiltration, as well as reverse osmosis (RO) (Katibi et al. 2021). Importantly, membrane filtration offers a significant advantage in conserving juice's nutritional content and flavor, while simultaneously eliminating undesired compounds, for instance, macromolecules and microorganisms. Thus, it yields a clear and transparent juice plentiful in nutrients and has an extended shelf life (Zhao et al. 2017). Combining membrane filtration operations with other interesting techniques has been proposed as a substitute for traditional methods in fruit juice (Akhtar et al. 2020; Panigrahi et al. 2022).

Many studies have been conducted on using membrane processes to manufacture fruit juices, particularly apple, orange, pineapple, Vietnamese, and kiwifruit juices. These studies have focused on investigating various processing parameters such as temperature, operating pressure, feed

concentration, pH, and crossflow velocity, in addition to examining the quality attributes of the resulting juice (clarity, nutritional content, color, and pH) (Bhattacharjee et al. 2017; Mai 2017; Conidi et al. 2020).

However, pomelo fruit has undergone limited processing in industrial trials; no studies have explored the application of membrane technology for processing pomelo juice. Besides, the study of the effect of this technology on the clarity of pomelo juice, preservation of bioactive compounds, and potential fouling issues is highly indispensable.

In this study, we investigate the use of membrane-based clarification methods for the processing of pomelo juice as well as the recovery of its bioactive compounds. Additionally, the study will focus on evaluating the effectiveness of different membrane processing parameters in improving the clarity of the juice while preserving the bioactive compounds and the fouling issue that might interfere.

Materials and methods

Pomelo juice preparation

Fresh pomelos were sourced from a market in Kajang, Selangor, Malaysia. The fruits were physically unclad using a sharp knife, cut into smaller pieces, weighed, and mixed with 100 mL of distilled water with a ratio (1:1) for 2 min. The extract was sifted *via* a cheesecloth before centrifugation under 9000 rpm for 15 min at ambient temperature.

The liquid left after centrifugation, known as raw pomelo juice, was utilized as a feed source for the enzymatic preliminary treatment and the ultrafiltration (UF) procedure.

Enzymatic pretreatment

Before the ultrafiltration (UF) process, a 500 mL sample of raw pomelo juice was treated with an enzyme. The enzyme utilized was pectinase (EC 3.2.1.15) derived from *Aspergillus niger*, which had an activity level of 3800 unit/mL and was obtained from Sigma-Aldrich, Merck, located in St. Louis, MO. Different enzyme concentrations were applied, namely 0.1%, 0.2%, 0.3%, 0.4%, and

0.5% by sample volume. A sample was created as a control group not exposed to enzymatic treatment. The samples that underwent enzymatic treatment were kept in a water bath (903, Protech Electronic, Malaysia) at 33 °C for a duration of 108 min, as stated by (Sagu, Karmakar, et al. 2014; Sagu, Nso, Karmakar, et al. 2014). Following the enzymatic treatment, the enzyme in the samples was deactivated by heating the samples at 95 °C for 5 min, as described by Sagu, Nso, et al. (2014). Afterwards, the samples underwent centrifugation at 9000 rpm for 10 min using the Eppendorf 5804 R instrument from Germany to separate the suspended solids. The resulting supernatants were then examined to determine their viscosity prior to undergoing the ultrafiltration (UF) process.

Ultrafiltration experimental procedures

Using a 250 mL laboratory-grade membrane stirred cell unit (Amicon[®], Millipore, USA) connected to an N₂ gas cylinder, the ultrafiltration (UF) experiment was carried out. The system contained a dead-end disk membrane crafted from polyethersulphone, with a molecular weight cutoff (MWCO) of 100 kDa, which effectively clarifies natural juices and agricultural by-products (Castro-Muñoz et al. (2018)). The temperature was kept at the ambient level (20 °C) throughout the experiment. Table 1 provides the membrane composition employed in this study to clarify the pomelo juice. To establish the optimum operating pressure (P_{lim}) required for the batch concentration mode and to achieve the superior permeate flux, each ultrafiltration (UF) test was carried out using varying operating pressures (OP) of 1.0, 1.5, 2.0, 2.5 and 3.0 bar.

Table 1. Experimental results fitting on distinct fouling models of the pectinase-treated sample (d) model I; (e) model II; and (f) model III.

OP (bar)	R^2		
	Model I (1/J)	Model II (1/J ²)	Model III (LnJ)
1.0	0.8432	0.8542*	0.7187
1.5	0.8972	0.9626*	0.7512
2.0	0.9496	0.9785*	0.8299
2.5	0.9689	0.9762*	0.8625
3.0	0.9461	0.9947*	0.848

*Indicates the highest R^2 for each experimental data block.

For each run, the filtration process was continued until 80% permeate recovery (PR) was reached to ensure the process ran efficiently, following Eq. (1);

$$PR(\%) = \frac{V_p}{V_f} \times 100 \quad (1)$$

V_p and V_f are the volume (g) of the permeate and the feed. The efficiency of the ultrafiltration system was assessed based on the permeate flux (J), which was calculated following Eq. (2);

$$J = \frac{1}{A_m} \times \frac{\Delta W}{\Delta t} \quad (2)$$

Equation (2) provided calculates the permeate flux (J) by dividing the permeate weight collected (ΔW) over a period of time (Δt) in units of kg.h⁻¹ by the effective membrane area (A_m) in square meters (m²).

Membrane cleaning

The measurement of pure water flux (J) involved introducing distilled water into the membrane module and quantifying the volume of collected permeate (ΔW) within a specified time (Δt) across the membrane surface area (A_m), as expressed in Equation 2. The pure water flux values were graphed against the applied transmembrane pressure (TMP) values to determine hydraulic permeability. The slope of the resulting straight line provided the hydraulic permeability of the UF membrane, referred to as Lp^0 for the fresh membrane. The membrane's hydraulic permeability after the Pomelo juice's UF process is represented as Lp^1 .

The membrane module cleaning procedure involves a two-step process. Initially, distilled water circulated through the membrane module for approximately 30 min at 3 bar pressure, aiming to minimize the impact of reversible cake layer resistance. The hydraulic permeability was then measured and denoted as Lp^2 . The module underwent a cleaning phase using a solution comprising 250 mL of 0.5 mM Sodium hypochlorite (NaOCl) in 0.5 M Sodium hydroxide (NaOH) for 20–40 min. Subsequently, a final rinsing was performed with distilled water for 5–10 min. Finally, the module was filled with distilled water and 10% ethanol and stored in a refrigerator at

approximately 4°C. The extent of membrane fouling, associated with the percentage drop in pure water flux after filtration, was determined by assessing the difference in pure water flux before the ultrafiltration treatment of pomelo juice and after the cleaning process.

Analysis of fouling behavior and mechanisms

Three fouling models were utilized to examine the fouling mechanism during the process, which consider the relationship between the alteration of permeate flux and filtration time (Conidi et al. 2020). The expression to characterize this relationship is described in Eq. (3);

$$J = \frac{J_o}{1 + J_o K t} \quad (3)$$

Where J_o represents the initial permeate flux while K and t are a coefficient and time, respectively. By using Eq. (3), various equations were developed for distinct fouling mechanisms, as illustrated in the following models;

Model I

Cake build-up fouling caused by the nature and properties of the membrane, as shown in Eq. (4).

$$\frac{1}{J} = \frac{1}{J_o} + K t \quad (4)$$

Model II

Equation (5) explains the occurrence of cake formation fouling, where a layer of particles covers the entire surface of the membrane.

$$\frac{1}{J^2} = \frac{1}{J_o^2} + K t \quad (5)$$

Model III

Equation (6) demonstrates pore blocking fouling, where particles fully obstruct certain fractions of the pores;

$$\ln J = \ln J_o + K t \quad (6)$$

To evaluate the primary fouling pattern in the studied ultrafiltration (UF) process, the experimental data was examined using a linear regression function in Microsoft Excel 2022 (USA) to fit each model. The model that exhibited the

superior coefficient of determination (R^2) was subsequently computed.

Analysis of viscosity, pH, and total soluble solid content

This study assessed the superficial viscosity of pomelo juice trials by employing a rheometer with controlled stress/controlled strain capabilities (MCR 301; Anton Paar GmbH, Graz, Austria) that had a dual gap cylinder model (DG.26.7/Q1; Anton Paar GmbH). The shear rate utilized was within the range of 0–500 s⁻¹, which was proposed by Omar et al. (2020). Moreover, the juice's pH was measured using a pH meter (Con 700, Oakton, USA) calibrated with buffer solutions with pH values of 4 and 7. The Total Soluble Solids (TSS) were also evaluated by means of a digital refractometer (RP-101, Atago, Tokyo, Japan), with the results expressed in °Brix units.

Analysis of total phenolic content (TPC)

The study utilized a colorimetric method to investigate the TPC in the pomelo juice samples. The method employed was the Folin-Ciocalteu assay, which operates by reducing a Folin-Ciocalteu reagent in the presence of phenolic compounds under alkaline conditions. Approximately 0.3 mL of the pomelo juice sample was blended with 1.5 mL of 10% Folin reagent (diluted with 90 mL of distilled water) and 1.2 mL of 7.5% sodium carbonate, Na₂CO₃ (prepared by dissolving 7.5 g of Na₂CO₃ in 100 mL of solution). A Shimadzu UV-VIS spectrophotometer (Ultraspec 3100 Pro, Amersham Pharmacia Biotech, UK) was employed to measure the solution's absorbance at 765 nm, and gallic acid was used to generate the standard curve. The total phenolic content was subsequently expressed in mg/L as a gallic acid equivalent.

Analysis of ascorbic acid content

Before titration against dichlorophenolindophenol (DCPIP) solution, the pomelo juice sample was diluted with distilled water (1:1 v/v) ratio. The titration was performed until a pink color

surfaced and lasted for at least 30 s, indicating the endpoint. The mass of ascorbic acid (in milligrams) present in the sample was computed using the volume of the titrated DCPIP solution.

Statistical analysis

The filtration process of pomelo juice was repeated twice, and all measurements were conducted three times. The collected data was analyzed by utilizing the Statistical Analysis System (SAS) software (Version 9.2, SAS Institute, USA) with a one-way analysis of variance (ANOVA). To determine the significance of differences in means, a p -value less than 0.05 was considered significant and compared using a t -test at a 5% significance level.

Results and discussion

Influence of enzymatic pretreatment on the viscosity of juice

The result of enzymatic pretreatment of the pomelo juice is presented in Figure 1. Figure 1 exhibits that the viscosity of the pomelo juice was considerably decreased by 35–54% after the application of pectinase in comparison to the unprocessed sample. This result suggests that pectin is a significant polysaccharide component in pomelo juice. Since the presence of pectin (polysaccharide) causes an elevated viscosity, the pectinase enzyme has been extensively utilized during the processing of fruit juice to hydrolyze

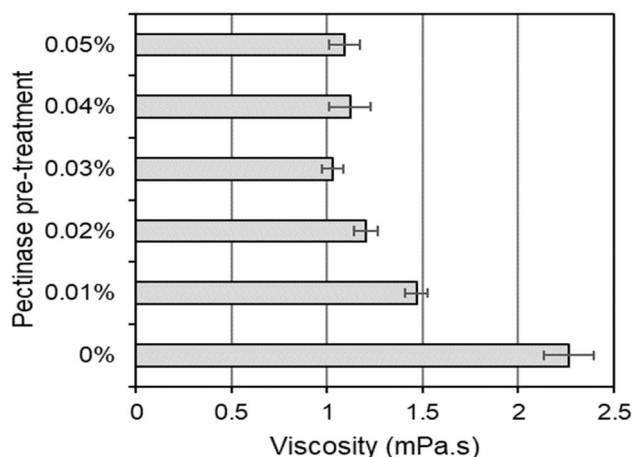


Figure 1. Apparent viscosity of untreated and pectinase-treated pomelo juice.

the galacturonan support of pectic polysaccharides of plant tissues to gain a lesser juice viscosity (Omar et al. 2020). Having a low viscosity is highly desirable when processing juice since it makes it easier to carry out the next steps in the process, such as clarification.

Figure 1 shows that there was no significant variation in the apparent viscosity of pomelo juice when different proportions of pectinase (ranging from 0.01% to 0.05%) were considered. This could be due to the level of pectin that exists in the juice. The concentration of pectin in juice may be lower, and as such, 0.02% pectinase is adequate to break it down. Based on the findings of this study, 0.02% pectinase has been selected as the treatment for pomelo juice for succeeding UF procedure.

Evaluation of permeate flux behaviour

The result of flux behavior is displayed in Figure 2. With reference to Figure 2, 1.0 bar OP demonstrated the least starting flux (59.9 kg/m²/h) as well as required the lengthiest time to attain 80% permeate recovery, under 60 min. Contrastingly, at 3.0 bar OP, the highest initial flux of 92.93 kg/m²/h was obtained, and the process was accomplished in 44 min. This occurrence was anticipated because the rise in permeate flux under pressure was caused by a greater driving force across the membrane, which was consistent

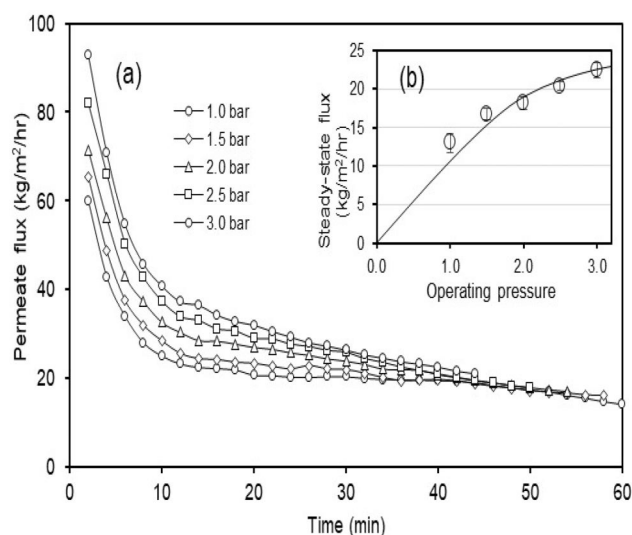


Figure 2. Permeate flux (J) profiles (a) J against time (t) at different operating pressures (OP); (b) steady-state J against operating pressure.

with previous findings regarding the juice filtration of bananas (Yee et al. 2021) and guava (Omar et al. 2020).

In Figure 2(a), it was observed that all flux profiles underwent three stages of flux reduction, with decreasing trends toward the end of the process, eventually reaching stable condition values across all operating pressures. The initial phase of the process involved a significant decrease in flux, which persisted for approximately 10 min. The subsequent phase saw a smaller decrease in flux, followed by a stable phase where the permeate flux remained constant over time until reaching its final value. The observed patterns were closely associated with the fouling occurrence that occurs on the membrane surface while filtering.

During the filtration, the gel polarization occurred as the feed navigated *via* the membrane, leaving suspended solids behind. Consequently, these suspended solids were deposited on the membrane surface, leading to fouling and a subsequent reduction in the flux rate. According to Omar et al. (2020), the flux rate at a steady state generally rose with an increase in pressure between 1 and 2 bar, as demonstrated in the inset of Figure 2.

According to Castro-Muñoz et al. (Castro-Muñoz et al. 2018), P_{lim} is the point at which fouling and polarization-concentration begin to exert a greater influence on the permeation rate than the driving force. The present study observed that the steady-state flux continued to increase even at the highest OP of 3.0 bar (Figure 2(b)), suggesting that the P_{lim} of this process lies beyond that value. It is possible that the enzymatic pretreatment facilitated a higher P_{lim} in this study by reducing the fouling issues.

Membrane cleaning performance

The result of the PES membrane cleaning with respect to hydraulic permeability is presented in Figure 3. The initial flux at the beginning of the experiment represents the membrane's performance under normal conditions prior to pomelo fruit juice clarification. The initial flux was 70 Kg/h/m² under a TMP of 1.0 bar. The flux rose to 104 Kg/h/m² under a TMP of 3.0 bar. The

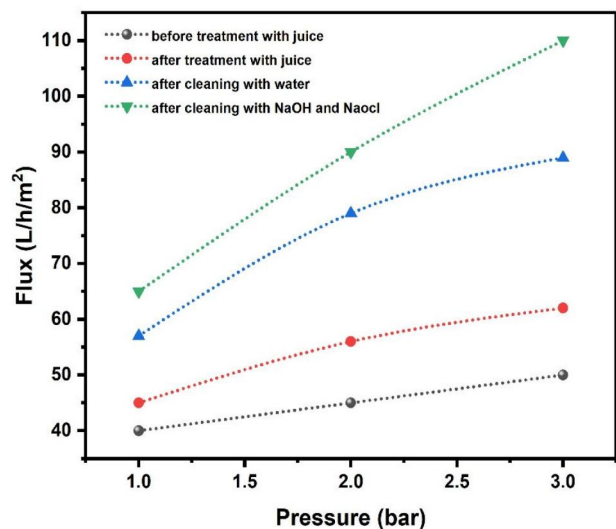


Figure 3. Pure water flux of membrane before and after UF and cleaning treatments.

membrane was then subjected to a flux test using pomelo fruit juice as a feed stream. The hydraulic permeability flux declined to 40 Kg/h/m² and 53 Kg/h/m² under 1.0 and 3.0 bar TMP, respectively, after the pomelo fruit juice clarification test, compared to the initial flux. This is because during the clarification of pomelo fruit juice, substances such as pectin, proteins, or other macromolecules may be present and can contribute to forming a cake layer on the membrane, reducing its permeability. Perhaps particles or substances in the fruit juice could block the membrane's pores and reduce the effective pore size, limiting the passage of water through the membrane. After that, the flux was slightly recovered upon membrane cleaning using distilled water and rose to 45 and 64 Kg/h/m² with TMP of 1.0 and 3.0 bar, respectively. The result obtained in this study is consistent with previous studies (Rabuni et al. 2015; Zhang et al. 2021). The moderate recovery in flux after cleaning with water indicates that some fouling was reversible but not completely removed. Water cleaning might have removed loosely attached particles or substances from the membrane surface.

Subsequent cleaning with NaOCl and NaOH further significantly advanced the flux recovery, thereby attaining 65 kg/h/m² and 110 kg/h/m² with TMP of 1.0 and 3.0 bar respectively. The most significant enhancement in flux is observed after cleaning with NaOH and NaOCl. The

substantial recovery after the more intensive cleaning with NaOCl (hypo) and NaOH (alkaline) solutions implies the successful removal of fouling agents, resulting in enhanced membrane performance. This underscores the efficiency of the cleaning method, which includes NaOCl and NaOH, in effectively removing reversible fouling from the membrane surface. Thus, the intensive cleaning process is an effective strategy in restoring the membrane's permeability.

Investigation of permeate flux decline mechanism

Fruit juices comprise a significant quantity of large molecules like polysaccharides (including pectins, hemicellulose, starch and cellulose) and particles that can cause turbidity (such as suspended solids (SS), proteins, polyphenols and colloidal particles); they may promote the development of fouling. Therefore, it is important to manage the operational pressure and other process parameters to prevent negative effects on the flux efficiency, as reported by Bhattacharjee et al. (2017). In order to ensure successful membrane filtration in the food industry, it is crucial to thoroughly examine the mechanism of membrane fouling that can hinder the process. Table 1 compares three models (referred to as model I, model II, as well as model III) in line with previous studies (Omar et al. 2020), which consider the relationship between changes in permeate flux and filtration time. By comprehending these models, we can enhance our ability to identify and address issues related to membrane fouling (Cassano et al. 2007).

The most appropriate model to describe the experimental data can be determined by identifying the model with the highest R^2 value among all samples. Model II was found to be the excellent model to describe the flux profiles due to its superior R^2 value, with R^2 (0.8542) at 1.0 bar and R^2 (0.9947) at 3.0 bar, compared to models I and III. According to model II, the primary cause of membrane fouling is the deposition of a cake on the entire membrane surface due to the accumulation of particles. This cake development during the filtration of pomelo juice is expected due to the numerous large molecules in fruit juice, such as polysaccharides, suspended solids, proteins and

colloidal particles (Omar et al. 2020). As indicated in Table 1, a higher R^2 (0.9947) was recorded at elevated OP (3.0 bar). This could be because, at higher operating pressures, there was a more significant amount of non-permeating molecules absorbed on the surface of the membrane, resulting in complete blockage of the pores. In this study, despite pre-treating the juice with pectinase enzyme, the same fouling mechanism remained dominant during the UF process. However, the resulting cake formation is classified as reversible fouling, indicating that appropriate cleaning measures can restore membrane permeability (Sagu, Nso, et al. 2014).

Investigation of the quality of the clarified pomelo juice

Analysis of pH and total soluble solid

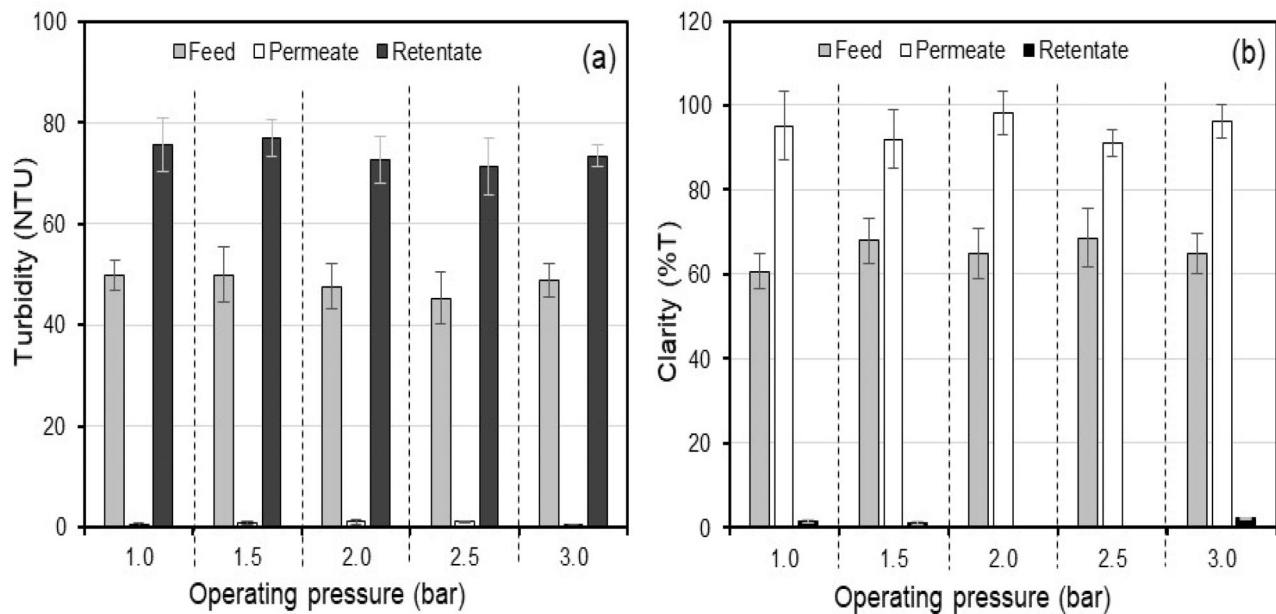
Table 2 displays the outcomes for pomelo juice's pH and overall soluble solid content. The pH level of the juice afterwards the clarification procedure (as shown in Table 2) does not exhibit any significant alterations. This suggests that the UF process does not have an impact on the pH status of the clarified pomelo juice, which aligns with previous research on the clarification of fruit juices (Conidi et al. 2020; Omar et al. 2020; Yee et al. 2021).

Table 2 demonstrates that the ultrafiltration (UF) method effectively decreased the total suspended solids (TSS) content in the filtered pomelo juice by a range of 7–17%. Although there is no apparent correlation between organic pollutants (OPs) and the reduction of TSS in the permeate, the result implies that the UF system efficiently eliminated certain suspended particles from the pomelo juice. This observation is confirmed by the fact that the retentate of all samples exhibited higher TSS levels than the feed, indicating that the membrane retained the soluble solids. A decline in the flux was due to concentration polarization which can also be linked to the concentration of TSS of the retentate solution. This decline can be attributed to the fouling deposits that developed from a blend of suspended solids as well as adsorbed large molecular impurities (Mai 2017).

Table 2. Results of pH and TSS of the pomelo juice subjected to UF under varying operating pressures.

Operating pressure (bar)	pH			TSS		
	Feed	Permeate	Retentate	Feed	Permeate	Retentate
1.0	4.02 ± 0.01 ^a	4.05 ± 0.05 ^a	3.97 ± 0.02 ^a	6.42 ± 0.4 ^a	5.72 ± 0.68 ^b	6.60 ± 0.29 ^a
1.5	4.04 ± 0.02 ^a	3.97 ± 0.06 ^a	3.98 ± 0.03 ^a	7.95 ± 0.55 ^a	6.92 ± 0.27 ^b	8.23 ± 0.55 ^{ac}
2.0	4.04 ± 0.03 ^a	3.96 ± 0.04 ^a	3.99 ± 0.01 ^a	7.20 ± 0.59 ^a	6.15 ± 0.53 ^b	8.05 ± 0.45 ^c
2.5	3.94 ± 0.01 ^a	3.91 ± 0.05 ^a	3.91 ± 0.03 ^a	8.05 ± 0.69 ^a	7.48 ± 0.33 ^b	8.47 ± 0.51 ^a
3.0	3.88 ± 0.03 ^a	3.91 ± 0.01 ^a	3.89 ± 0.02 ^a	7.55 ± 0.46 ^a	6.22 ± 0.41 ^b	7.68 ± 0.32 ^a

*Means (± SD) with the distinct letters are significantly different at $p < 0.05$ for each row of the section.

**Figure 4.** UF pomelo juice properties at different operating pressures (a) turbidity; (b) clarity.

Analysis of turbidity and clarity

Turbidity, which refers to the cloudiness or haziness of a liquid, is a major factor contributing to a decrease in quality during the processing and storage of juices in the industry. The cloudiness in fruit juice is the presence of polysaccharides, including hemicellulose, pectin, and starch, which tend to settle down gradually during storage. Figure 4(a,b) represent the results of turbidity and clarity of pomelo fruit juice under varying operating pressure of 1.0–3.0 bar. After undergoing the UF process, the turbidity of the permeate was almost eliminated. The turbidity content of the feed juice (unfiltered) ranged between 45.30 and 50.0 NTU, respectively (Figure 4(a)). Distinct turbidities contents (0.50–1.10 NTU) were obtained after filtration. Among the five operating pressures applied (1.0–3.0 bar) in pomelo juice, 3.0 bar resulted in the lowest turbidity (0.50 NTU) (Figure 4(a)). All the filtered samples displayed a turbidity reduction of more than

97%, leading to a significantly clearer pomelo juice.

The elimination of turbidity in the clarified juice can be linked to a decrease in TSS. Turbidity typically indicates the existence of suspended particles, fibers, high molecular weight carbohydrates, and TSS, according to Castro-Muñoz et al. (2018). Most non-permeable molecules are gathered on the membrane surface during the UF process, leading to elevated turbidity and TSS levels in the retentates.

The enhancement of pomelo juice's physical attributes, precisely its clarity, holds great importance as consumers highly value the appealing appearance of fruit juice. Juice that exhibits a clear and visually appealing appearance is more likely to be preferred and consumed by the public (Castro-Muñoz et al. 2018). The removal of turbidity has resulted in a significant improvement in the clarity of the pomelo juice. The clarity results are shown in Figure 3(b). There was a

Table 3. Results of total phenolic content (TPC) and ascorbic acid content (AAC) of pomelo juice subjected to UF under varying operating pressures.

Operating pressure (bar)	TPC (mg/L)			AAC (mg)		
	Feed	Permeate	Retentate	Feed	Permeate	Retentate
1.0	75.15 ± 5.58 ^a	65.68 ± 3.23 ^b	73.39 ± 2.62 ^a	48.12 ± 3.61 ^a	42.05 ± 3.22 ^b	47.08 ± 2.46 ^a
1.5	79.05 ± 4.12 ^a	68.08 ± 2.71 ^b	73.32 ± 2.53 ^c	45.13 ± 4.02 ^a	40.07 ± 2.36 ^{ab}	44.10 ± 4.50 ^a
2.0	80.02 ± 6.67 ^a	73.76 ± 4.60 ^b	76.23 ± 3.10 ^b	50.17 ± 4.01 ^a	44.07 ± 2.41 ^b	44.11 ± 3.46 ^b
2.5	85.66 ± 5.87 ^a	75.10 ± 4.70 ^b	82.41 ± 1.85 ^a	49.18 ± 2.76 ^a	40.98 ± 3.39 ^b	42.10 ± 4.30 ^b
3.0	88.22 ± 6.03 ^a	79.30 ± 3.66 ^b	81.01 ± 2.55 ^b	47.22 ± 3.03 ^a	42.11 ± 1.29 ^b	43.11 ± 4.36 ^b

*Means (± SD) with the different letters are significantly different at $p < 0.05$ for each row of the section.

significant increase in the clarity of the juice after the filtration process. The transmission values of the filtered pomelo juice sample showed an increase of 95.17%, 91.92%, 98.29%, 91.04%, and 96.23% for the juice filtered at 1.0, 1.5, 2.0, 2.5 and 3.0 bar, respectively, which resulted in a better juice clarity. The increased clarity of pomelo juice produced a visually cleanse output. Fruit juice with a clear appearance is more attractive and pleasant for public consumption (Omar et al. 2020).

Total phenolic content (TPC) and ascorbic acid content (AAC)

The results of total phenolic content (TPC) and ascorbic acid content (AAC) are presented in Table 3. In general, filtering pomelo juice resulted in a decrease in TPC, with reductions of 12.6%, 13.9%, 7.8%, 12.3%, and 10.1% observed when the process was carried out at operating pressures of 1.0, 1.5, 2.0, 2.5 and 3.0 bar, respectively. To achieve a clear extract, it is essential to reduce the levels of turbidity and total solids, but this can lead to a decrease in polyphenols, which can undermine the nutritional value of the extract (de Santana Magalhães et al. 2019). While the loss of nutritional value in the juice is not ideal, other research has also observed similar outcomes. This has been attributed to oxidation and interactions with other compounds not retained by the membranes (Castro-Muñoz et al. 2018; Omar et al. 2020).

The decline in TPC that was observed in the permeate could be due to the reaction of compounds that were restricted from passing through the membranes (Castro-Muñoz et al. 2018). This loss of phenolic compounds could also be linked to the ongoing effects of polyphenol oxidases in the retentate (Zhao et al. 2014).

However, according to the results of this study, the reduction in TPC may not be influenced by changes in the operating pressure. Besides, the TPC of the juice is not only indicative of its antioxidant properties but also related to its astringency. As a result, the observed reduction of TPC in this study suggests a decrease in the clarified juice's astringency, which could be viewed positively in terms of sensory perception.

Under varying operating pressures, the AAC in the permeate was reduced than that in the feed. The AAC decreased by 12.6%, 11.2%, 12.2%, 16.7%, and 10.8% at operating pressures of 1.0, 1.5, 2.0, 2.5 and 3.0 bar, respectively. Nevertheless, the decrement is deemed to be minor as most of the ascorbic acid was still preserved in the filtered juice. Similar to TPC, the AAC is thought to be independent of changes in operating pressure.

Appraisal with previous studies

Table 4 summarizes various findings regarding the clarification of different fruit juices. The results indicate the efficacy of varying membrane processes in treating fruit juices, with each specific condition and membrane type showing varying degrees of performance in removing turbidity, TSS, and phenolic content. The comparisons across different studies provide valuable insights into the potential applications of membrane technology in fruit juice processing. The present study achieved a significant reduction in turbidity (>97%), indicating the effectiveness of the UF process in clarifying suspended particles. This result aligns with the high removal percentages reported in studies on Guava (Omar et al. 2020) and Dragon Fruit (Le et al. 2021), where turbidity removal exceeded 97%. The present study reported a slight reduction in Total

Table 4. Findings of previous studies with the present study.

Fruit Juice	Membrane process	Operating variables	Membrane type	Performance (Turbidity, TSS and Phenolic content)	References
Guava	UF	80% permeate recovery; TMP: 200 kPa;	PES, flat sheet, 32 cm ² , 100 kDa	>97.00; 82.54; 79.62	(Omar et al. 2020)
Pomegranate	MF	T: 25 °C; Q: 30 L/h	PVDF, hollow fiber, 27.6 cm ² , 0.13 µm,	100; 99.09; 96.45	(Morittu et al. 2020)
Cashew apple	MF	T: 25 ± 2 °C; TMP: 138 kPa; Q: 10 L/h	PSF, hollow fiber, 0.2 µm, 51.8 cm ²	96.70; 96.93; 48.92	
Mosambi	MF	T: 28 ± 2 °C; TMP: 69 kPa	PA, flat sheet, 2.5 µm, 28.3 cm ²	97.80; 91.40	(Singh and Das 2021)
Tomato	MF	TF: 26 °C; PF: 200 kPa; PVac: 5 kPa	Al ₂ O ₃ ceramic, tubular, 392 cm ² , 0.2 µm,	98.13	(Alaei et al. 2021)
Dragon fruit	UF	T: 25 °C; CFV: 0.02 m/s, TMP: 300 kPa	PES, flat sheet, 6.15 cm ² , TMP:10 kDa,	Highest permeate flux (7.9 kg m ⁻² h ⁻¹), least retention of betacyanins (30.6%) and phenolic compounds (11.3%),	(Le et al. 2021)
Pomegranate	MF	T: 20 °C; Q: 0.6 L/h, TMP: 50.66 kPa	Cellulose ester, flat sheet, 78 cm ² , 0.22 µm	71.64; 80.00; 55.56	(Zarouk et al. 2022)
Pomelo	UF	T: 20 °C; TMP: 3 bar; Q: 92.93 Kg/h/m ²	PES, flat sheet, 100 kDa	A significant reduction in turbidity of over 97%, TSS (7–17%); minor decline in TPC (10.1–13.9%) AAC reduction (10.8–16.7%)	Present study

Phenolic Content (TPC) (10.1–13.9%), which is consistent with the findings from studies on Tomatoes (Alaei et al. 2021) and Pomegranate (Zarouk et al. 2022) where the removal of phenolic compounds ranged from 10.8% to 16.7%. The slight decline in TSS (7–17%) for Pomelo juice observed in the present study is comparable to the results reported in other studies, such as Pomegranate (Morittu et al. 2020) and Dragon Fruit (Le et al. 2021) where TSS removal was highly effective.

Hence, compared to other studies, the present study's performance in turbidity reduction, TSS removal, and phenolic content reduction demonstrates the effectiveness of UF in improving the quality of Pomelo juice. The results indicate that UF can be a reliable and efficient membrane process for treating various fruit juices, contributing to the growing body of knowledge on membrane technology applications in the food and beverage industry.

Conclusion

In this study, pomelo juice was clarified using a UF (Ultrafiltration) process, which yielded important information regarding the flux profile at varying operating pressures, fouling mechanisms, and quality traits of the juice. A pretreatment with 0.02% pectinase is adequate to reduce the juice viscosity. The operating pressure influenced the permeate flux in the UF stages, and the process's limit pressure (P_{lim}) is expected to be

more than 3.0 bar. Total pore blocking was determined to be the principal fouling mechanism of the UF process at all operating pressure. The UF process effectively clarified the pomelo juice by reducing TSS and turbidity while maintaining the pH. However, the permeates showed some reduction in TPC and AAC compared to the fresh juice due to oxidation and solute interactions. Despite this, the reduction in TPC could be considered a positive development since it is expected to decrease the juice's astringency. Considering the permeation flux profiles and juice quality characteristics, the ideal operating pressure to clarify pomelo juice for the UF process in this study appears to be 3.0 bar.

Disclosure statement

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