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Separation methods in the food industry: An exploration of reverse osmosis, evaporation and freeze concentration applications

[a]Nurul Amalia Farhana Abu Bakar, [a]Farah Hanim Ab Hamid*

[a]School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA, Selangor, Malaysia

*Corresponding email: farah88@uitm.edu.my

Abstract

Separation method is broadly used in various industries, mainly in the food industry. Some of the applications include retaining the nutrients and concentrating fruit juices, liquid foods, and milk products. Fundamentally, the concentrated liquid product is achieved by these separation methods. Technology advances daily, impacting food quality characteristics such as flavour, colour, and texture. Production and commercialisation processes are key considerations, from conventional to modern approaches. Hence, this study aims to review the various types of separation methods with their application in food industries which are evaporation, reverse osmosis, and freeze concentration that is separated into two: suspension freeze concentration and progressive freeze concentration.

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1.0 Introduction

The food industry is one of the vital industries in ensuring the sustainability of basic human needs. The growing need for internal quality assurance in the fresh industry has stimulated the production of a broad variety of advanced, quick, real-time, accurate, and non-invasive quality management technologies (Magwaza & Opara, 2015). Fruits are one of the most common sources of food that have been consumed by people since the beginning of time. As the technology progressed, concentrated fruit juice is produced in a mass number by the food industry. The interest in concentrated juice has escalated within the food industry due to the variety of its usage as ingredients in ice creams, fruit syrups, and fruit juice beverages (Cassano et al., 2004). The concentration of fruit juices requires the selective elimination of water without alterations in the structure of the solids, leaving all the initial solid elements, such as fruit sugars, minerals, and vitamins, to a more concentrated solution (Toribio & Lozano, 1986).

Concentrating fruit juice is one of the most common preservation techniques since it offers a variety of advantages, such as decreased volume or weight, decreased packing, better storage, ease of transport, and longer shelf life (Maskan, 2006). In placing more emphasis, Cassano et al. (2004) claimed that the concentration of fruit juices, a major unit operation in the fruit processing industry, is of vital significance as it defines the final product quality such as flavour, colour, scent, and appearance. Concentrated fruit juice often offers a longer lifespan to meet longer business operation periods, as well as improved conservation because of decreasing in water activity (Assawarachan & Noomhorm, 2010). Hence, an appropriate concentrating food method, including fruits are essential in retaining its quality and properties.

Essentially, the taste and appearance of food products have a huge influence on consumer acceptability (Ibrahim et al., 2012). Consumer eye on the quality of fruit and vegetables that affect the initial decision to buy is also focused on an external factor such as appearance, colour, structure, and size (Opara & Pathare, 2014). Henceforth, the separation method is essential in various industries, mainly in food industries. Evaporation, membrane concentration (reverse osmosis) and freeze concentration are three methods for the concentration of liquid foods (Sánchez et al., 2011). In the food industry, separation technology is widely used to extract, separate, and purify a single component from a mixture (Yongjae, 2015). The food processing industry uses numerous methods to convert food ingredients into various forms for users, without altering its nutrients and properties. Hence, it is important to carry out this study to review the various types of separation methods with its application as it is the most crucial unit operation in the food industry and give beneficial benefits towards the food industry.

2.0 Evaporation

Evaporation is one of the well-known methods in the separation process. Evaporation is a thermal process attributed to heat transfer theories, where the liquid food regulates the phenomenon since it has a significant resistance to heating. This method is used broadly in the dairy industry to purify milk, and to create fruit juice concentrates in the fruit juice industry as well as in the sugar industry to concentrate sugar mixtures for crystallisation (Toledo, 2007). Evaporation is the process that involves heating process mixture until no more liquid remains.

Osmotic evaporation (EO) is one of the methods applied in the evaporation technique to concentrate food. Osmotic evaporation (OE) is a type of membrane distillation (MD), the mechanism of which utilises hydrophobic membranes, where pores are filled with the gas phase of the fluid to concentrate, thereby blocking the passage of water such that only volatile components are transferred across the membrane (Castro Domingues et al., 2014).

Osmotic evaporation (OE), also called osmotic distillation or direct osmotic distillation which is a competitor of reverse osmosis (Kunz et al., 1996). Osmotic evaporation is a concentration technique for aqueous mixtures based on the use of macroporous and hydrophobic membranes, usually made of polytetrafluoroethylene (PTFE) or polypropylene (Romero et al., 2003). Osmotic evaporation portrays a modification of conventional membrane processes, whereby water is transported across the hydrophobic membrane as vapour, hence producing an extremely concentrated extraction solution (Forero Longas & Velez Pasos, 2011). The membrane concentration process mainly fit for the processing of heat-sensitive aqueous solutions such as fruit juices and pharmaceutical products (Hongvaleerat et al., 2008). The osmotic evaporation technique allows the removal of water from aqueous solutions via a driving force produced under pressure and temperature ambient conditions (Marques et al., 2017). Hongvaleerat et al. (2008) also expressed a similar view, in which this method has a huge ability for concentrating fruit juices because osmotic evaporation can be done at moderate temperatures and pressure thus possible to be a great potential for concentrating fruit juices. Although a temperature differential is produced among both sides of the membrane due to water evaporation on one side followed by condensation on the other side, osmotic evaporation is an isothermal process (Alves & Coelhoso, 2006). Energy consumption for osmatic evaporation is much smaller than compared to reverse osmosis (Kunz et al., 1996). Even though osmotic evaporation proved to obtain a concentrated juice with good physicochemical sensory, this method needs to be evaluated due to its low yields and long process times which is up to 8 hours (Forero et al., 2013). Fig. 1 shows an illustrated diagram for osmotic evaporation.

According to the study that has been conducted by Hongvaleerat et al. (2008), found that pineapple can be concentrated without altering the principal product quality criteria via the osmotic evaporation process. Table 1 shows the effect on the fluxes of water evaporation (N_w) of the temperature difference between the juice and brine (ΔT) and the brine (U_{brine}). Hongvaleerat et al. (2008) found that rising in temperature of the juice from 20 to 35 °C nearly doubled the flow of evaporation, while the rise in

Table 1: The effect on the fluxes of water evaporation of the temperature difference between the juice and brine (Hongvaleerat et al., 2008)

U_{brine} (ms^{-1})	T_{juice} (°C)	T_{brine} (°C)	ΔT $T_{juice}-T_{brine}$)	N_w ($kg \cdot h^{-1} \cdot m^{-2}$)
2.0	20	20	0	4.5
3.1	20	20	0	4.9
2.0	35	20	15	8.6
3.1	35	20	15	9.1

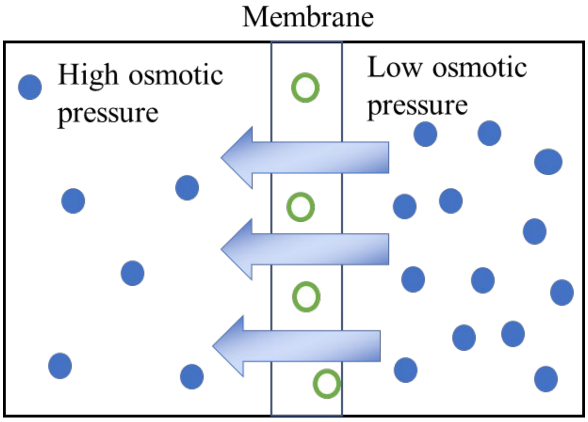


Fig. 1: Illustration of osmotic evaporation (Source: Author's illustration

velocity slightly increased the evaporation flux (about 7%). The improvement of flux with temperature was largely because of rising in partial water pressure on the liquid-gas interfaces on the juice side of the membrane, which boost the driving force for water transport (Alves & Coelhoso, 2002). Higher temperatures also decrease the viscosity of the feed stream creating a high liquid mass transfer coefficient (Hongvaleerat et al., 2008).

The interest of this membrane method was stressed compared to thermal evaporation, particularly intended for colour preservation that is commonly affected by thermal treatments (Rattanathanalerk et al., 2005). Rising in juice velocity increases osmotic evaporation efficiency and the improved homogeneity of the juice generated inside the fibre allows the less condensed solution to have more interaction with the membrane (Forero-Longas et al., 2017). These two situations led to greater differential vapour pressure on the surface and to the elimination of the condensed solution (viscous layer) which acts as a water transport resistance (Forero-Longas et al., 2017). Nevertheless, the residence time within the module may be reduced if the velocity rises too much (Rezakazemi et al., 2012). Apart from that, other findings showed that the osmotic evaporation method well preserves the aromatic compounds of the fruit juices during the concentration period (Cisse et al., 2005). Hongvaleerat et al. (2008) also stated that higher brine speeds and higher temperature gradients between the juice and the brine have been confirmed to be the most important working conditions with regards to the flux of water evaporation. Nonetheless, some research show higher brine velocities usage can cause membrane rupture and brine inflow to the juice side (Hongvaleerat et al., 2008). Hongvaleerat et al. (2008) clearly reported that there were no massive changes in the major properties of pineapple juice.

3.0 Reverse osmosis

Reverse osmosis (RO) is a method where water is transported throughout a membrane between two mediums that the water is flowing counter to the normal osmosis flow (Samsuri et al., 2016). RO replaced the evaporation method due to high yield and require minimum energy as no phase change occurs (Yahya et al., 2017b). Furthermore, RO is extremely energy-effective, as this process normally operates at ambient temperature, meaning that no heating and cooling are needed in the process (Lazarides & Katsanidis, 2003). To contrast evaporation and membrane processes, the usage of membrane concentrates was much more environmentally sustainable, and it could save up to 35% of the cumulative energy demand (Depping et al., 2017). Fig. 2 shows the illustrated diagram for the RO process.

RO is one type of concentrating food product, such as milk. In the dairy industry, RO is primarily used to concentrate liquid dairy streams (through dewatering) at a specified temperature (10 °C–40 °C) with no phase change (Deshwal et al., 2021). Dairy proteins are beneficial ingredients and as high-quality dietary additives, nutraceuticals, and therapeutics (Chollangi & Hossain, 2007). Essentially, certain proteins, lactose, and lipids are the primary constituents of milk (Mehta, 2015). Hence, reverse osmosis technology is used to measure the concentration of skim milk, by assessing the characteristics of the protein, lactose, and lipid, which can demonstrate the process efficiency.

Using reverse osmosis skim milk allows heat damage or denatured protein in contrast with evaporated condensed milk (DBV, 2004). Nanofiltration and reverse osmosis are more effective in terms of recovery of lactose, but greater operating pressures are needed as opposed to ultrafiltration (Patel & Murthy, 2012). Lactose can be used in the food and pharmaceutical

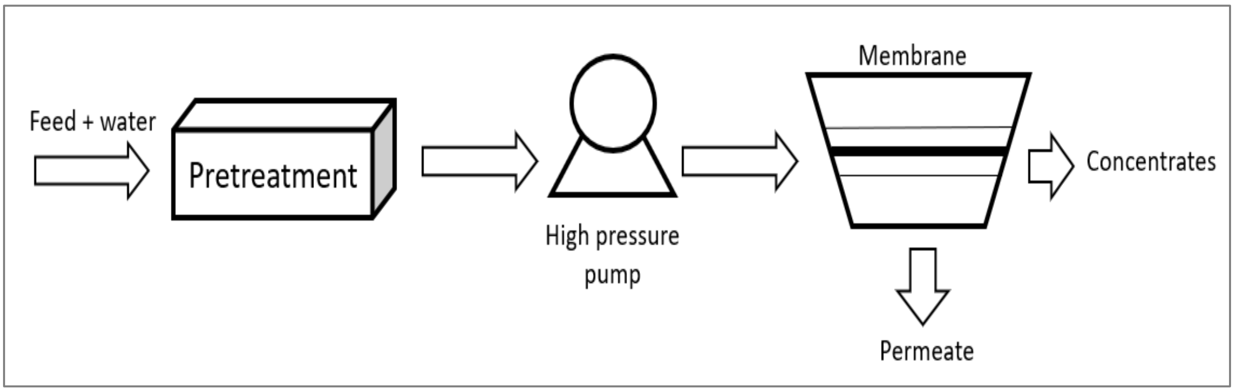


Fig. 2: Illustration of RO process (Source: Author’s illustration)

industries (De Souza et al., 2010). Other than that, skim milk lipid material has been measured in terms of distribution of particle size and lipid structure and contrasted to other distributions of milk fat particles (Jhanwar & Ward, 2014). Polar milk lipids have powerful nutraceutical properties (Spitsberg, 2005), such as enhancing the intestinal barrier against inflammation-induced hyperpermeability (Snow et al., 2011). A study by Arend et al. (2019) showed that retention value (%R) for protein was the highest 100%, followed by lactose with 99% and lastly lipid with 98.47%, meaning that reverse osmosis in skim milk concentration is truly efficient. Table 2 shows the protein, lactose, and lipid concentrations once the concentration process is completed.

Research on nanofiltration of tofu whey and pasteurised milk proved that the existence of substances with a large molar mass (such as proteins) could affect the selectivity of the membrane because of the adsorption and deposition of these compounds on the surface of the membrane (Benedetti et al., 2015). Arend et al. (2019) claimed that the deposition can modify the charge of the membrane, hence influencing the permeation of negatively or positively charged compounds. He also stated that protein degradation could have happened owing to deposition on the surface of the membrane. Milk proteins have a molecular diameter of around 6nm and are preserved by the membrane, confirming a 100% retention value (Fennema, 1987). Apart from that, a previous study by Meyer et al. (2017), comparing skim milk and whey, stated that the better protein content caused a better deposit forming and, in consequence, a greater effect of protein removal could be seen for skim milk relative to sweet whey.

Apart from that, the lactose retention value is 99%. This is supported by Brião & Tavares (2012), the high value is caused by membrane fouling that contributes to the significant membrane rejection of lactose. Balannec et al. (2005) also notified analogous lactose rejection values when using a reverse osmosis membrane, as well as Yorgun et al. (2008) stated the similar behaviour when evaluating ultrafiltration, nanofiltration, and reverse osmosis for whey treatment. Moreover, the lowest retention value is 98.47% which belongs to lipid concentrations. Even though their molecular size is larger than the membrane molar mass cut-off (MMC), lipid permeation is bigger due to their nonpolar nature (James et al., 2003). Hydrophobic solutes are more simply adsorbed to the membrane surface as opposed to hydrophilic solutes (Jönsson & Trägårdh, 1990). Additionally, the membranes had pores density of various sizes, such that any of the lipids could migrate through the membrane (Brião & Tavares, 2012). Concerning the efficiency of reverse osmosis in skim milk concentrations, it was found that the percentage of retention of all constituents surpassed 98%, meaning that the reverse osmosis method can be utilised as a pre-concentration step to attain a product at the same time the nutritional quality is preserved (Arend et al., 2019).

Table 2: The composition of protein, lactose, and lipid concentrations in completed RO process. (Arend et al., 2019)

Sample	Protein (%)	%R	Lactose (%)	%R	Lipid (%)	%R
Skim milk	2.99	100	6.410	99.97	0.150	98.47
Conc.	5.19		12.390		0.250	
Perm.	0.00		0.003		0.004	

4.0 Freeze concentration

Freeze concentration (FC) is a method presented intentionally to improve the concentration of a solution (Samsuri et al., 2016). Another common name for freeze concentration is cryoconcentration. FC is an improved technology that suits in separating the various solvent from the solution, together with its ability to boost the concentrated solution (Yahya et al., 2017a). In simple terms, FC extracts water from liquid food and solutions by freezing (Orellana-Palma et al., 2017). According to Miyawaki & Inakuma (2021), in FC, high purity ice is ideally formed in the process, implying that complete component concentration is predicted. Three steps are participating in the FC process which are the formation of ice crystal, growth of ice crystal, and lastly the division of the ice crystals and the solution (Miyawaki et al., 2016). The objective of FC is to form extremely pure ice crystal, meaning that only water without any solids is preserved in the ice crystal (Hernández et al., 2010). One of the advantages of FC is that there is no volatility loss as this method does not require high temperature and the vapour-liquid interface does not occur (Petzold & Aguilera, 2013). FC enables the processing of high-quality food concentrates compared to evaporation and membrane technologies (Petzold & Aguilera, 2013).

The importance to achieve commercial viability is by using assisted techniques or external forces that enhance the freeze concentration process (Petzold et al., 2019). This study focuses on centrifugal which is an assisted technique in freeze concentration. Centrifugal freeze concentration is a cryo-concentration process aided by external force centrifugation, to improve the concentrate separation from the ice (Orellana-Palma et al., 2017). Basically, the freeze concentration supported by an external force (such as centrifugation) utilises the hydraulic arrangement that occurs in the frozen matrix between the ice crystals occluding the solutes (Orellana-Palma et al., 2017). Centrifugation is a separation type in which the gravity force is effectively substituted by a higher driving force with the application of centrifugal force (Toledo, 2007). The method benefited from the hydraulic mechanism in the frozen matrix created by veins (or channels) between ice crystals occluding the concentrated solution (Petzold & Aguilera, 2013). The matrix in the frozen framework is accountable for variations in the impurity's concentration in ancient polar ice, where solutes circulated through the microchannels within ice crystals under the stress of the upper ice layers (Rempel et al., 2001).

In an article by Orellana-Palma et al. (2019a), centrifugation was used as an efficient aided method to maximise the performance and concentration of the solute usually removed using three cryo-concentration cycles and subsequently boost process parameters with efficiencies between 60% and 75%. Fig. 3 shows the standard experimental procedure with three cryoconcentration cycles for orange juice.

Specifically, the centrifugal cryoconcentration emphasised the concentrated fraction, then removing the ice fraction, and the benefits of restoring the cryoconcentrate between ice crystals in each phase (Orellana-Palma et al., 2019b). Nevertheless, until today, the centrifugal freeze concentration needs three cycles, which means a significant freezing period for each sample, huge energy costs of repetitive freezing and centrifugal methods, and eventually, a decreased final amount of concentrated fraction is reached (Orellana-Palma et al., 2019a). Some difficulties need to be addressed in centrifugal cryoconcentration in terms of final solute, separation, and procedure parameters in the ice fraction (Orellana-Palma et al., 2019a).

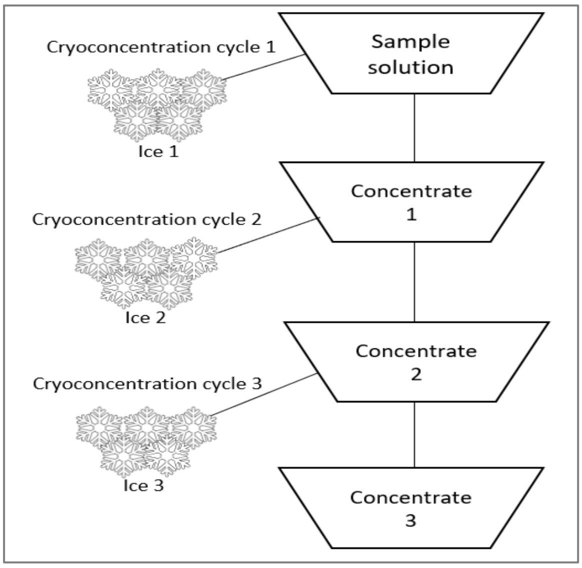
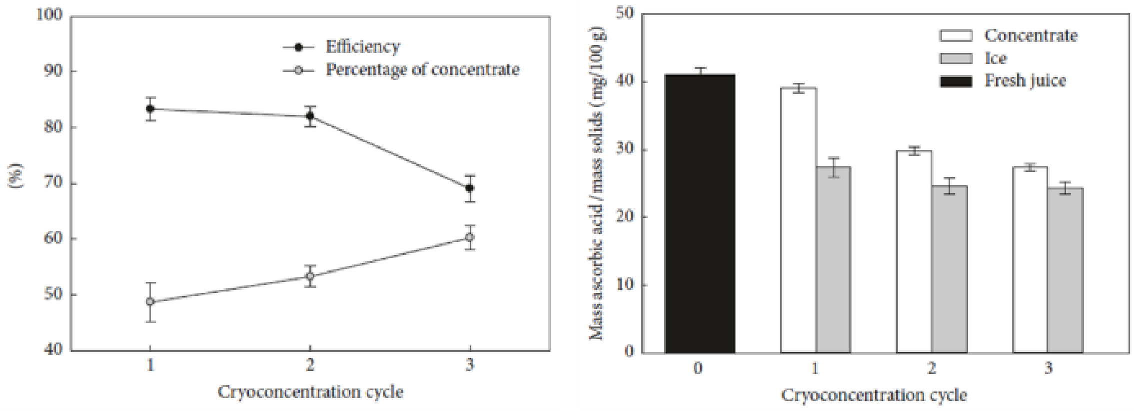


Fig. 3: Standard experimental procedure with three cryoconcentrations (Source: Author's illustration)

A gradual rise in the percentage of concentrate was found after the concentration cycles for orange juice and achieved 60% (Orellana-Palma et al., 2017) which was similar to the values recorded in the literature by Petzold et al., (2015). These findings are clarified by the hypothesis that the percentage of concentrate is a mathematical direct function of the original concentration of solutes in the sample to the centrifugal freeze concentrate, thus, as the rise in the cryoconcentration cycles (and the increase in the concentration of solutes) is predicted to boost the percentage of concentrate (Petzold & Aguilera, 2013). By referring to efficiency in Fig. 4(a), the efficiency decreases while the concentrate percentage (%) increases gradually over the cycle. The efficiency was reduced due to a rise in the initial concentration at each cryoconcentration cycle (Orellana-Palma et al., 2017). Apart from that, freeze concentration process performance typically drops as a function of the process stages due to higher retaining of solutes in the ice (Belén et al., 2012). In addition, Hui (2004) stated that the greater the concentrate solid, the greater the viscosity, and the freezing concentration quality usually relied on the viscosity of the concentrate. The efficiency values obtained (80– 70%) were close to the data obtained by Adorno et al., (2017) obtained an efficiency of nearly 78% for strawberries concentrated by this modern method.

On the other hand, for ascorbic acid content in Fig. 4(b), feed orange juice had an ascorbic acid value of roughly 41 mg/100 g of solids and claimed that as the cycle increases, the content of ascorbic acid decreases steadily even though as predicted, higher presence of ascorbic acid content in the concentrated period (Orellana-Palma et al., 2019a). This reduction of ascorbic acid content is clarified by the fact that the process of centrifugal freezing requires the withdrawal



(a) (b)

Fig. 4: Development of (a) efficiency and percentage of concentration as a function of the cryoconcentration cycle, (b) the ascorbic acid content in the concentrated and ice fractions as a function of the cryoconcentration cycle (Orellana-Palma et al., 2017)

of the resultant ice in each phase, which is the removal of the existing solutes and hence of ascorbic acid (Orellana-Palma et al., 2017). The concentrate reaches a value of nearly 28 mg/100 g solids at the third cycle. A similar study has been conducted by Aider & de Halleux (2008) who used apricot and cherry juices, there was no major degradation of ascorbic acid as resulted by using a sub-zero temperature to concentrate the juice. Hence, it clearly shows that centrifugal freeze concentration is useful in obtaining a high-quality concentrate from orange juice.

4.1 Suspension freeze concentration

Suspension freeze concentration (SFC) technology is a viable alternative to conventional chaptalisation technology (Zhang et al., 2016). SFC is a freeze concentration process where the ice crystals are developed in a suspension of the mother liquor and is characterised by the generation of mass distribution of crystal growing at constant temperature (Jusoh et al., 2008). Throughout SFC, the ice growth and degree of supercooling are sustained by constantly seeding the suspension with new crystals (Vuist et al., 2020). Apart from that, Ding et al. (2019) found that in SFC, ice crystals are suspended in a bulk solution and developed, creating a two-phase fluid of ice and mother liquor, also known as ice slurry. In general, a conventional SFC consists of three phases which are an ice nucleator, a re-crystalliser, and an ice crystal separator (Jusoh et al., 2014a).

At present, only scraped surface heat exchangers (SSHE) have been used for liquid foods (Ding et al., 2019). The ice nucleator that is normally used in SFC is SSHE that is essentially creating ice nuclei and sustains maximum heat transfer by scraping the ice layer produced meanwhile the limited size of ice crystals that are created from the scraping procedure need an extra step to increase the ice crystal size (Jusoh & Mohamed Nor, 2014). The tiny size of the ice produced in this process allows it tough to detach from the mother solution and needs a very complex system to widen and to achieve a standard size of the ice crystals formed (Jusoh et al., 2014b). Furthermore, the size of ice crystal is still limited in the SFC process (Gu et al., 2006) and the SFC process needed a complicated SSHE that is extremely pricey and accounted for almost 30% of the capital cost (Jusoh et al., 2008). Apart from that, this method is said to be a complicated process because it combines SSHE, crystalliser as well as wash column (Ding et al., 2020). Hence, researchers find ways to improvise this method as SFC is correlated with high operating and investment cost (Samsuri et al., 2019), such as combining SSHE, crystalliser, and wash column into one equipment, which can be applied in concentrating apple juice (Ding et al., 2019).

Basically, the SSHE develops ice nuclei at large supercooling times and low residence times, where ice nuclei are produced on the inner surface of the heat exchanger and then scraped off by spinning blades subsequently the ice nuclei go to the re-crystalliser for ice crystal formation (Sánchez et al., 2009). Ice is normally created with an SSHE chilled by an evaporating cooling system where ice dendrite is developed on the cooling surface and scraped off and combined with a bulk solution (Dass & Grenco, 1991).

The efficiency of the scraped surface heat exchanger is substantially influenced by how ice crystallisation happens on the walls of the SSHE (such as the structure and growth behaviour of the ice formed) and by the rate at which this occurs (Ben Lakhdar et al., 2005). This is supported by Qin et al. (2006), the development of ice on the cooling surface, behaving as a fouling layer, influences the heat transfer coefficient of SSHE. Ice particles removed from the cooling surface, mix with the bulk liquid, and create a greater viscosity crystal suspension (Qin et al., 2006).

Moreover, aromatic components and vitamin content can be found in apple juice concentration. The aromatic component represented in apple juice was butyl acetate. The apple juice concentration and butyl acetate content rise after three-step freeze concentrator (FC) and they may be perceived to be a synchronous rise (Ding et al., 2019). Apart from that, the retention rate of butyl acetate is 90.2% (Ding et al., 2019), which is compatible with other studies of the FC apple juice sensory characteristics study (Miyawaki et al., 2016). Nevertheless, in comparing with evaporation concentration (EC), the EC juice concentration improves but the butyl acetate content rises slightly, with a 38.9% retention rate, initiating a large flavour loss when it is altered (Ding et al., 2019). Hence, in the contemporary advanced EC method, distillation or stripping equipment must be utilised to retrieve the volatile aromatic condensate and restore it to the juice concentrate to minimise the loss of flavour and authenticity (Saffarionpour & Ottens, 2018).

Apart from that, the retention rate of vitamin C in FC was 90.4% while in EC was 84.5% due to the degradation of vitamin C involving aerobic and anaerobic pathways (Ding et al., 2019). The aerobic pathway is important in the concentration of apple juice, however, anaerobic degradation is slight and does not drastically alter with temperature (Mercali et al., 2014). This is supported by Johnson et al. (1995), the dissolved oxygen level of apple juice is very poor, thereby inhibiting the degradation of vitamin C under vacuum EC (60°C). Hence, it is proven the aromatic components and content of vitamin C in apple juice improved nearly uniformly with a rise in the concentration of juice compared to EC (Ding et al., 2019). The combined SSHE, crystalliser, and wash column proposed in this research may resolve the above limitations by modifying the FC equipment to reduce the operation cost (Ding et al., 2019).

4.2 Progressive freeze concentration

Progressive Freeze Concentration (PFC) is a type of FC in which ice crystals are developed in a form of a layer on the surface of the crystalliser and produce only a single huge form of ice block instead of many small ice crystals (Ab Hamid & Jami, 2019). In the PFC system, the concentration method is the removal of solute from the moving ice front which is the boundary between the ice and solution phases (Samsuri et al., 2016). Apart from that, the solution that needs to be concentrated moves throughout a cooled surface hence crystallisation process happens on the surface of the crystalliser (Yahya et al., 2015). The PFC method is much easier compared to SFC where a large single ice crystal is developed and expanded on the wall of the crystalliser (Samsuri et al., 2019). Hence, separation among the ice crystal and the concentrated solution in the PFC method indeed becomes incredibly uncomplicated.

According to Mazli et al. (2020), PFC was developed since it provides a simpler process for separation and requires less maintenance. This can be supported by Ab Hamid et al. (2019), in the PFC method, the separation of ice crystal from its mother liquor is much simpler to be controlled contrasted to SFC as only a single ice crystal is produced. PFC is more accommodating than SFC since SFC is an incessant process requiring extremely long residence time compared to PFC that only operates in a repetitive batch system with a relatively short cycle (Gu et al., 2006). One essential factor that contributes to influencing the efficiency of the system is the design of the crystalliser where the ice crystallisation takes place (Jusoh et al., 2009), such as anti-supercooling holes crystalliser to concentrate sugarcane juice (Yahya et al., 2017a). Fig. 5 shows the illustrated diagram for the anti-supercooling holes crystalliser. Theoretically, the supercooled product is volatile, and random nucleation will occur at any time (Fukuma et al., 2012) which

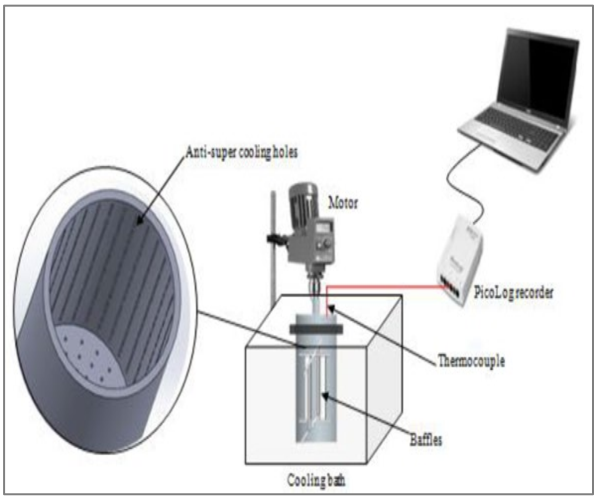


Fig. 5: Illustration of anti-supercooling holes crystalliser (Ab. Hamid et al., 2015)

causes contamination of ice crystals, leading to poor quality, which is detrimental to the system (Ab Hamid & Jusoh, 2013). Essentially, the ice nucleation is linked to the process of avoiding supercooling in the crystalliser, which was equipped with holes (Ab Hamid & Jusoh, 2013). The holes offer space for the nucleation and ice crystals of pure molecules, where the molecules are cooled down to below the freezing point earlier than the normal bulk solution molecules, as they are almost in touch with the wall that is chilled by the coolant. In addition, there would be a greater possibility of ice nucleation and a smaller probability of the contaminant being retained in the ice owing to the higher freezing point of pure water molecules as opposed to the solution comprising foreign solute molecules (Liu et al., 1998). The ice formed in these holes also produces more high-purity ice crystals. The benefit of this design is ice lining method may be ignored, allowing it simpler to work (Ab. Hamid et al., 2015).

Effective partition constant (K) is one of the crucial parameters that need to be reviewed to determine the PFC performance. Fundamentally, K determines the performance of the process which is linked to the quality of the ice generated. As K rises, the efficiency of the PFC process eventually will be low (Amran & Jusoh, 2016). Research conducted by Yahya et al. (2017a) on sugarcane concentration, coolant temperature of −8 ℃ is deemed as optimum temperature as the K value is the lowest. This study has found a similar result with (Ab. Hamid et al., 2015). In addition, it has drawn attention to the fact that a lower K value indicates that large ice purity has been generated in which more soluble solutes stay in the concentrate. This statement is strongly supported by Amran & Jusoh (2016) that stated lowering the coolant temperature will result in a minimal K value but maximal in solute recovery value. It is best to have a low K value to get the optimum efficiency of the PFC process. Nevertheless, Yahya et al. (2017a) found that

Table 3: The pros and cons of common separation methods in the food industries

Separation methods	Concept	Type of food application	Advantages	Disadvantages
Evaporation	Applied similar concept as dehydration which used to remove water from food product.	• Pineapple juice (Hongvaleerat et al., 2008) • Milk (Azzaro-Pantel et al., 2022)	Easy to operate.	The process requires high temperature that possibly damage the vital composition in the mixture.
Reverse Osmosis (RO)	Comprising membrane to preconcentrate fruit juices to avoid heating which subsequent in minimum thermal damage.	• Skim milk (Arend et al., 2019) • Buttermilk (Krebs et al., 2023) • Peach juice (Li et al., 2022)	Energy-effective, no heating and cooling needed in the process.	Membrane easily blocked.
Freeze Concentration (FC)	Separating water from liquid food by freezing along with its ability to improve concentrated solution.	• Orange juice (Orellana-Palma et al., 2017) • Tofu whey (Benedetti et al., 2015)	High retention of volatile aroma and process at low temperature.	Costly than evaporation and reverse osmosis.
Suspension Freeze Concentration (SFC)	Ice crystals are suspended in bulk solution and developed which eventually generating a two-phase ice fluid and mother liquor.	• Apple juice (Qin et al., 2021)	High efficiency and high final concentration obtained.	Limited ice crystals size and very complicated system.
Progressive Freeze Concentration (PFC)	Ice crystals are generated in layer form around the crystallizer surface which later only single huge form of ice block produced, rather than many small ice crystals.	• Sugarcane juice (Yahya et al., 2017a) • Cucumber juice (Mohd Rosli et al., 2022) • Cheese whey (Uald Lamkaddam, et al. 2023)	Low maintenance cost and the process much easier compared to SFC.	Less efficiency compared to SFC.

the K value rose as the temperature was too low (−8 °C to −14 °C), hence the sugarcane concentration efficiency of the system was reduced. In addition, the coolant temperature affects the ice growth rate, where a minimal growth rate will increase the purity of the generated ice (Ab. Hamid et al., 2015). According to Amran & Jusoh (2013), as the difference between the inlet solution and the surface temperature rises, the ice growth rate also rises. In this case, entering temperature applies to the temperature of the solution, such as sugar cane juice within the crystalliser, whereas the surface temperature belongs to the temperature of the coolant (Yahya et al., 2017a). Consequently, more solute will be retained in the ice, which decreases the purity of the ice generated. Therefore, it is proven that coolant temperature decreased obviously will boost the efficiency of the PFC process (Ab Hamid & Jami, 2019). Table 3 shows the comparison for every separation method utilised in the food industry.

5.0 Conclusion

The applications of separation technology in the food industry are wide. Numerous innovative technological changes within the food industry have propelled the initiative in obtaining the highest quality products whilst preserving the nutrients. Evaporation, reverse osmosis, and freeze concentration which can be divided into suspension freeze concentration and progressive freeze concentration are the common . separation methods. Even more research study requires to concentrate on food products from various sources or types of food. Essentially, a suitable choice of separation method brings an impact on the process efficiency. Selecting the separation method in food industry should concern quality, food characteristics, the process used during the production, and commercialisation. Thus, it is vital to understand the various types of separation methods available and their application in food industries.

Contribution statement

Nurul Amalia Farhana Abu Bakar: Conceptualisation, Methodology and Writing-Original Draft. **Farah Hanim Ab Hamid**: Conceptualisation, Methodology and Writing-Reviewing and Editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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