REVIEW OF LITERATURE

CHAPTER II

REVIEW OF LITERATURE

This chapter reviews the previous research works carried out by research workers, scientists and students. Review related to cocoa and its composition, therapeutic values, processing of coca, pulp extraction and wine ageing methods, HC assisted ageing of wine, operating parameters of various techniques and applications are included in this chapter.

2.1. PLANTATION CROPS

High-value commercial crops known as "plantation crops" are essential to the agricultural economies and export markets of both industrialized and developing nations. The commercial features of farming these crops gain significant economic relevance as a result of the World Trade Organization's increased emphasis on agriculture. The main products cultivated on a plantation basis include arecanut (betel nut), cardamom, cashew, cocoa, coconut, coffee, oil palm, rubber and tea. These crops need a lot of effort to cultivate and are perennial in nature. During numerous on-farm operations and off-farm processing activities, their cultivation offers significant job prospects both directly and indirectly. The most noticeable feature of plantation crops is that they are monocultures, with the same crops grown in sizable, adjacent areas, typically in stands of uniform age. Coffee, cocoa, arecanuts, and coconuts are an exception, as they can be cultivated as multiple crops or as a mono crop. These crops are primarily grown in the tropical zone between 20°N and 20°S of the equator (Chopra *et al.,* 2017).

Over the past few decades, plantation crop production and area have steadily increased. The productivity of the main plantation crops has steadily increased, much like area and production. The availability of enhanced crop production and protection methods, improved varieties, coordinated efforts to disseminate technology, and institutional backing are the primary causes of the productivity improvement (Anandaraj and Dinesh, 2015).

2.2 COCOA

In addition to being a crop used to make beverages; cocoa is the primary component used to make chocolate. Cocoa mass is used to make chocolate and confections, and cocoa beans are the source of cocoa butter. An alkaloid called Theobromine gives stimulating properties to cocoa (Chopra *et al.,* 2017). Because of its rich nutrient content and shown health benefits, cocoa is considered a super food. One of the most widely consumed foods is cocoa and products made from it, which are rich in vital elements such as minerals, protein, fat, carbohydrates, and polyphenols. Bioactive substances can also be found in cocoa. Polyphenols, which are made up of both flavonoids and non-flavonoids, are the main bioactive ingredients. Rich in antioxidants and anti-inflammatory properties, the bioactive ingredients support a number of health advantages. Chocolates high in flavonoids enhance peripheral vascular function. Consuming chocolate or cocoa helps to prevent the intricate molecular mechanism that causes cancer (Shahanas *et al.,* 2019).

The cocoa fruit is a pod that weighs between 200 g and over 1 kg and has colours that vary from green to purple when the fruit is unripe to red, orange, or yellow when it is ripe. Their size varies between 10 and 35 cm, and their shape differs based on the type. Cocoa pods are composed of an inside mucilage called pulp that envelops the seeds and an external component called husk. The four layers of cocoa pod husks (CPH), which make up roughly 67–76% of the entire fruit, are the epicarp (or peel), mesocarp, sclerotic portion, and endocarp. The outer shell (cocoa bean shell, or CBS), two cotyledons (nibs), and the germ make up cocoa beans, which make up 33% of the entire fruit (Mariatti *et al.,* 2021).

Cocoa is a crucial component of many meals consumed in industrialized nations, including chocolate, cakes, biscuits, kid-friendly cuisine, ice cream, and sweets (Guehi *et al.,* 2007). The pharmaceutical and cosmetics industries make extensive use of cocoa butter, also known as cocoa fat (Anvoh *et al.,* 2009).

2.2.1 Production statistics of cocoa

Theobroma, the general name for cocoa, literally translates to "Food of the Gods". Known as "black gold", cocoa is mostly grown in Asia, Latin America, and West

Africa. Eight of the 45 countries that grow cocoa account for around 90% of global production. About 70% of the world's cocoa production comes from the six million hectares of cocoa planted in the West African forest zone. The top producers at the moment are Ghana and Ivory Coast, followed by Nigeria and Cameroon. From around 20,00,000 tons in 2000 to roughly 30,00,000 tons in 2010 and later years, cocoa production increased (Wessel and Foluke, 2015). Currently, global cocoa production and consumption stand at approximately 2.7 million metric tons, while India's production is relatively low at just 10,000 metric tons (DCCD, 2021).

2.2.2 Cocoa mucilage

Mucilage, a material that covers the cocoa seeds, has long been utilized as a substrate for the fermentation of the cocoa beans and is crucial for the production of precursor compounds with flavour and aroma. Because it contains minerals including calcium, iron, potassium, magnesium and zinc as well as vitamins B, C, D and E, this by-product of cocoa processing has a high nutritional and functional value (Soares and Oliveira, 2022).

According to numerous research, the use of cocoa mucilage has been increased substantially in recent years. Numerous derivative goods, such as wines, vinegars, jellies, ice creams, gels, marmalades and alcoholic and non-alcoholic beverages, have been developed as a result of these studies (Puerari *et al.,* 2012). Cocoa mucilage also has a lot of potential for producing pectin, which makes it a perfect ingredient for making marmalades and jellies consistent. A new revenue stream for cocoa producers has been made possible by the rise of cocoa mucilage as a valued market product (Barazarte *et al.,* 2008).

During cocoa bean fermentation, mucilage undergoes metabolism as it contains bacteria and yeasts that play a crucial role in breaking down sugars. These microbes contribute to the creation of substances that enhance the organoleptic properties of cocoa and give chocolate its distinct flavour profile (Ngoc *et al.,* 2022).

The pulp from the beans can be removed to improve the quality of seeds by lowering their acidity. Cocoa pulp juice has been successfully used to make beer, vinegar, and jelly (Abballe *et al.,* 2021). The extracted cocoa pulp is essentially regarded as agroindustry waste and is discarded into the environment, but it can be used to create a variety of goods especially wine (Ngangoum *et al.,* 2022).

2.2.3 Cocoa Wine

Many societies have strong cultural and historical links to wine. For centuries, it has been connected to social gatherings, religious rites, rituals, and festivals. Around the world, traditions and rituals have been greatly influenced by the production and consumption of wine (Harutyunyan and Ferreira, 2022). Esters, high alcohols, fixed acidity (citric, tartaric, and malic acid), sugars, aldehydes, tannins, pectins, vitamins and minerals are among the many organic and inorganic substances that make up this complex mixture. It is an alcoholic beverage produced by fermenting must with wine yeasts from grape juice or other fruits (Nemzer *et al.,* 2021).

The mucilage from cocoa beans is extracted, wine is made from the mucilage using *Saccharomyces cerevisiae* as a starter, and the wine's microbiological, physicochemical, and sensory qualities are assessed (Ngangoum *et al.,* 2022).

2.2.4 Fermentation

Fermentation is a practical method for creating new goods with altered physico-chemical and sensory characteristics particularly flavour and nutritional components. Among these, alcoholic fermentation is frequently used to make drinks that contain a significant quantity of alcohol. Increased shelf life and reduced reliance on refrigeration or other food preservation technologies are two benefits of fermentation which is a low-energy, effective preservation method. As a result, it is a very suitable technique for usage in rural locations and developing nations with limited access to advanced technology. Worldwide, fermented fruit wines are well-liked, and in some areas, they account for a sizable portion of millions of people's diets. In addition to ethanol, alcoholic fermentation produces a number of byproducts. They include acids, acetals, esters, alcohols, and carbonyl compounds, all of which have an impact on the final quality of the product. The composition and concentration levels of the by-products can vary substantially (Saranraj *et al.,* 2017).

2.3 AGEING OF WINE

"Wine aging" refers to a collection of processes that take place after wines are bottled. The process of storing wine prior to bottling is referred to as wine maturation. The wine may mature for six to twenty-four months or for several years. Clarification may be used at this point while accounting for the potential for malolactic fermentation in the wine. The process of wine aging, which begins with bottling of wine, is also known as reductive aging as it takes place without oxygen. Numerous reactions that had taken place during wine aging led to notable organoleptical alterations in wine. The most noticeable alteration in the colour of wine during the maturation and aging process is caused by phenolic alterations. The following processes enable the phenolic alterations that take place in wines both before and after production. These are degradation of anthocyanin, interactions of tannin with proteins, tannin reactions with polysaccharides, cation formation of procyanidine, oxidation and polymerization reactions of procyanidin, anthocyanin copigments formation processes, anthocyanin reactions with compounds that contain polarized double bonds and anthocyanin condensation reactions with tannins. Various research has concentrated on innovative wine aging methods that will reduce the aging period and preserve the quality of wine after aging. It is also considered as an alternative to oak barrel aging. These methods involve applying certain physical treatments and micro-oxygenating the wines. Every strategy can help with distinct aspects of the wine-aging process. Wine aging can be done with the help of gamma irradiation, electric fields and ultrasonic vibrations. The goal of studies employing these techniques is to provide consumers with high-quality wines while reducing the amount of time that wine must age (Hatice and Ezgi, 2017).

2.4 CAVITATION

Cavitation refers to the process where microbubbles or cavities form, grow, and then collapse within a very short time frame (milliseconds), releasing significant amounts of energy at the site of transformation. Cavitation can be viewed as a complex phenomenon made up of various dynamic components that interact independently. It generates extremely high energy densities (energy released per unit volume) locally, leading to intense pressures (ranging from 100 to 5,000 bar) and temperatures (ranging from 1,000 to 10,000 K), with these effects occurring at millions of points within the reactor (Suslick, 1990). Cavitation also leads to the creation of highly reactive free radicals, ongoing cleaning and an increase in the surface area of solid catalysts. It also improves mass transfer rates due to the turbulence created by liquid circulation currents (Lorimer and Mason, 1987 and Luche and Cintas, 1999). Additionally, cavitation intensities can be controlled with relatively low energy inputs to achieve the desired chemical or physical transformations.

Cavitation can be categorized into four primary types based on how the cavities are generated. These are particle, optic, acoustic and hydrodynamic cavitation (Gogate *et al.,* 2006). Among these, particle and optic cavitation techniques are typically used to produce single bubble cavitation, which does not cause significant physical or chemical changes in the bulk solution.

2.4.1 Optic cavitation

Optic cavitation is achieved by passing a pulse of laser light through a transparent medium. This process is a form of thermo-cavitation, where heat is generated in the area where the light beam is focused, raising the temperature above the boiling point of liquid. As the temperature reaches the spinodal limit of the liquid, density fluctuations occur, leading to the rapid formation of expanding bubbles. These bubbles eventually collapse due to the uneven conditions over a very brief period of time. However, since boiling is a bulk phenomenon, the localized temperature increase around the bubbles does not cause the entire liquid to reach its boiling point in such a short time. Typically, bubble formation and collapse occur when the bubbles come into contact with the solid surface of the container or reactor. This process can be used for applications such as surface cleaning, luminescence, and generating mechanical shock waves (Martinez *et al.,* 2014).

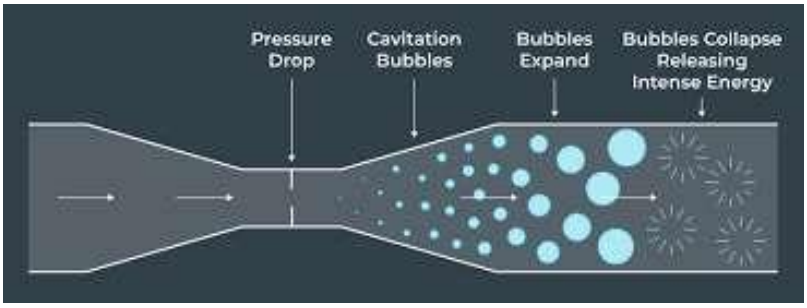
2.4.2 Particle cavitation

Particle cavitation occurs when significant thermal stresses develop between two phases of a material with different thermal expansion coefficients. The extent of cavitation can be regulated by adjusting the cooling rate of the matrix (Serpooshan *et al.,* 2007). This phenomenon is commonly observed in systems composed of two distinct phases: a dispersed phase and a continuous phase. Due to their differing thermal properties, the formation and collapse of vapor bubbles behave uniquely in each phase. In this scenario, no single mechanism solely governs bubble collapse. Therefore, controlling the cooling rate of the liquid medium is essential to ensure the vapor condenses back into the liquid, thus providing effective control over the cavitation process.

2.4.3 Acoustic cavitation

Acoustic cavitation uses ultrasound to concentrate energy into small volumes. As the ultrasound waves pass through the medium, they cause bubbles to oscillate between compression and expansion due to pressure fluctuations. This oscillation leads to the diffusion of gases and vapours in and out of the bubbles. Additionally, particle cavitation induces physical stresses, including bubble collapse, thermal shock, and the formation of high-velocity water jets. This process can generate extreme conditions, with temperatures reaching thousands of Kelvin and pressures in the GPa range. Hydraulic cavitation systems and devices can efficiently produce such effects by forcing a liquid through a constriction, such as a venturi, orifice, or throttling valve (Capocelli *et al.,* 2014).

2.4.4 Hydrodynamic cavitation



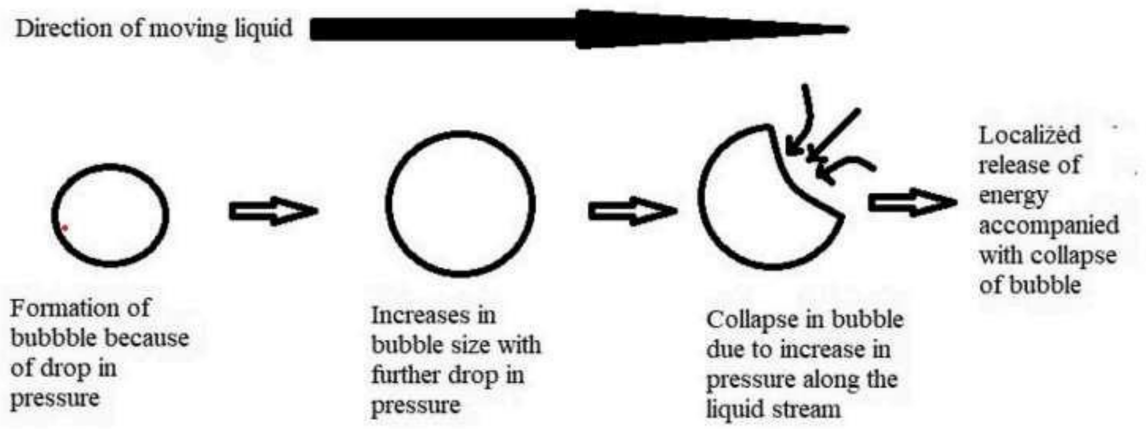
(Source: Gogate *et al.,* 2001)

Fig.2.1. Graphical illustration of hydrodynamic cavitation

Hydrodynamic cavitation is generated by pressure fluctuations caused by changes in the flow velocity of a liquid. It occurs when liquid passes through a constriction, such as an orifice or venturi, or when an object rotates within the liquid. The behaviour of hydrodynamic cavitation bubbles closely resembles that of acoustic cavitation bubbles. Hydrodynamic cavitation presents several benefits, including costeffective scalability, low capital investment, and high operational efficiency. Consequently, it serves as a promising alternative to acoustic cavitation (Gogate *et al.,* 2001) and has been widely applied in commercial processes for intensification (Holkar *et al.,* 2019).

2.4.4.1 Principle of hydrodynamic cavitation

Cavitation is a complex heterogeneous process composed of dynamic components that interact independently. It involves the intentional formation, expansion, and rapid collapse of bubbles within milliseconds. This phenomenon results from the interplay of multiple factors, releasing a substantial amount of energy near the collapsing bubbles. Consequently, it generates extreme localized conditions, with pressures ranging from 100 to 5000 bars and temperatures between 1000 and 10,000 K.



(Source: Gogate *et al.,* 2001)

Fig. 2.2. Principle of hydrodynamic cavitation

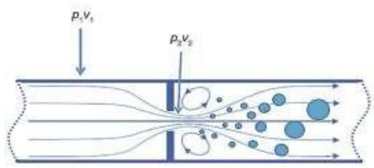
This process occurs simultaneously at multiple sites within the reactor. It can lead to both beneficial and undesirable effects, such as the formation of reactive species like free radicals, an increase in the surface area of solid catalysts and enhanced mass transfer rates. Initially, hydrodynamic cavitation (HC) was viewed as an unavoidable nuisance in liquid systems, often causing mechanical erosion. Many studies were conducted to minimize this phenomenon, but with proper equipment design, it is now possible to utilize cavitation for various energy efficient applications. Additionally, cavitation intensities can be controlled with relatively low energy inputs to achieve the desired chemical or physical transformations.

2.4.4.2 Mechanism of hydrodynamic cavitation

Cavitation bubbles, or cavities, form when the local pressure falls below the liquid's vapor pressure. Bernoulli's principle provides insight into achieving this pressure reduction within a flow system. The relationship between liquid velocity and pressure distribution in a flow field is described by Eq. (2.1). To facilitate cavitation, a constriction is often introduced in fluid pathways, accelerating the fluid and inducing a pressure drop at the constriction.

$$P_1+\frac{1}{2}\rho_1 V_1^2 = P_2+\frac{1}{2}\rho_2 V_2^2 \quad (2.1)$$

Here, ρ represents the fluid density, P_1 and P_2 are the pressures at two points (typically upstream and downstream, respectively) in a flowing system, and V_1 and V_2 are the corresponding fluid velocities, as illustrated in Fig.2.3. As the liquid flows through the tube, its velocity increases while the pressure decreases. At the narrowest point of the system, known as the throat, the liquid reaches its maximum velocity (V_2), and the pressure (P_2) drops to its minimum value.



(Source: Sarc *et al.,* 2017)

Fig.2.3. Mechanism of hydrodynamic cavitation

Vapor bubbles are believed to form when the local pressure drops below the liquid's vapor pressure at a given temperature (Sarc *et al*., 2017). If P_2 falls below this threshold, cavitation bubbles can develop. As the fluid moves downstream of the constriction, a sudden pressure recovery occurs, leading to bubble collapse and the release of substantial energy. The lower the pressure at the throat, the more intense the cavitation and the greater the energy output. Accurately predicting cavitation onset is crucial, as it not only enhances the understanding of cavitation physics but also aids in analyzing flow patterns during hydrodynamic cavitation and optimizing cavitation device design.

2.5 FACTORS AFFECTING CAVITATION

2.5.1 Temperature

Fluid temperature is a crucial factor in nucleation and cavitation across various processes, including chemical reactions, hot fluid injection, and cryogenic cavitation. Temperature influences cavitation flow in two contrasting ways. Increasing temperature at constant ambient pressure promotes liquid vaporization, making cavitation more likely. However, higher temperatures can also suppress cavitation by reducing vapor pressure within gas bubbles. Additionally, the latent heat of vaporization cools the surrounding liquid, further lowering the vapor pressure inside the bubbles. Additionally, higher temperatures generally reduce the solubility of gases in the liquid, which leads to a lower number of cavitation nuclei – the key factor in cavitation initiation. As a result, the threshold for initiating cavitation is raised.

Studies have shown that in chemically deoxidized water, cavitation intensity increases as temperature decreases, while higher temperatures lead to weaker cavitation. Similar observations were made by Torre *et al.* (2011), who proposed that thermal effects have an inverse relationship with cavitation intensity. This conclusion was based on the observation that degradation performance worsens with increasing temperature. Additionally, *Li et al.,* (2017) studied the effect of dissolved oxygen and nitrogen as cavitation nuclei on the tensile strength of water and found that higher gas concentrations lead to a greater likelihood of cavitation.

2.5.2 Pressure

Pressure plays a critical role in determining the onset of cavitation. Since vapor pressure and downstream pressure are commonly used to calculate the cavitation number in a flow system, analyzing the impact of inlet pressure is equally important. Although inlet pressure is relatively easy to measure and control, its influence on cavitation remained underexplored until the past two decades. Soyama (2021) studied the effects of upstream and downstream pressures on cavitation intensity using a venturi tube with water as the working fluid. His findings revealed that with a constant downstream pressure, the cavitation region expanded steadily as upstream pressure increased. Conversely, when upstream pressure was fixed, cavitation formed and intensified rapidly as downstream pressure decreased. Similarly, Kumar and Pandit (1999) observed highly turbulent downstream flow and violent bubble collapse at elevated inlet pressures, attributing this behaviour to the substantial pressure drop across the orifice caused by high inlet pressure.

2.5.3 Chemical effects

Extreme conditions are generated during the vapor collapse process. During cavitation, free radicals such as OH and H are generated as water molecules within the collapsing bubbles undergo dissociation. These radicals disperse into the surrounding fluid, where they can initiate chemical reactions or modify existing reaction mechanisms.

2.5.4 Mechanical effects

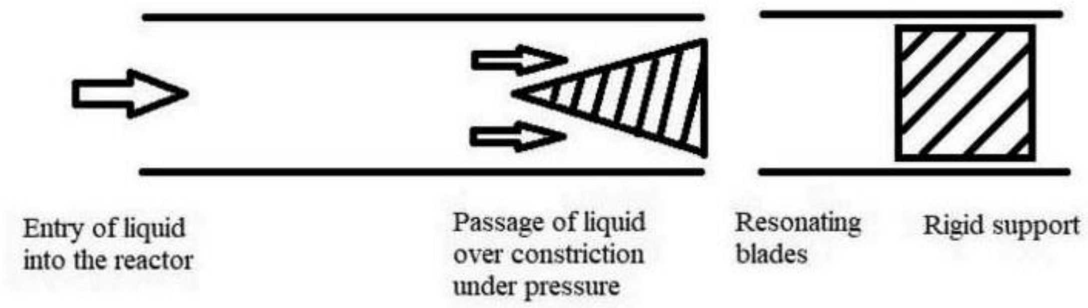
The mechanical effects of cavitation enhance reactions in gas-liquid systems. The intense temperature, pressure, and turbulence generated by collapsing cavitation bubbles lead to substantial structural and mechanical transformations. Additionally, mass transfer occurs not only between gas bubbles and the liquid surface but also at the interface between different liquid phases. Since millions of microscopic bubbles are created during cavitation, they produce powerful shockwaves that can damage materials when the bubbles collapse. For this reason, Gogate (2008) suggested hydrodynamic cavitation as a method to enhance mass transfer between liquids, as mass transfer at the interface is often the rate-limiting step in many heterogeneous reactions.

Inside a cavity, gases and vapours are trapped adiabatically, generating intense heat that raises the surrounding temperature and forms a localized hot spot upon collapse. Consequently, each collapsing cavity acts as a micro-reactor, where extreme temperature and pressure peaks cause entrapped organic molecules to thermally decompose into smaller fragments. Despite the exceptionally high temperatures in this region, the small scale of the cavity allows heat to dissipate rapidly, keeping the bulk of the liquid at a stable temperature.

Simultaneously, the oscillation and collapse of cavities generate high-shear micro jets and turbulence at the interface. This turbulence and mixing helps to distribute particles uniformly and facilitate their interaction, leading to the formation of fine emulsions. As a result, the surface area increases significantly, enhancing reaction rates. This leads to a faster reaction rate at the bubble-liquid interface compared to the bulk liquid. Additionally, cavitation-generated emulsions exhibit greater stability, often requiring minimal or no surfactants to maintain their structure.

2.6 HYDRODYNAMIC CAVITATION REACTOR

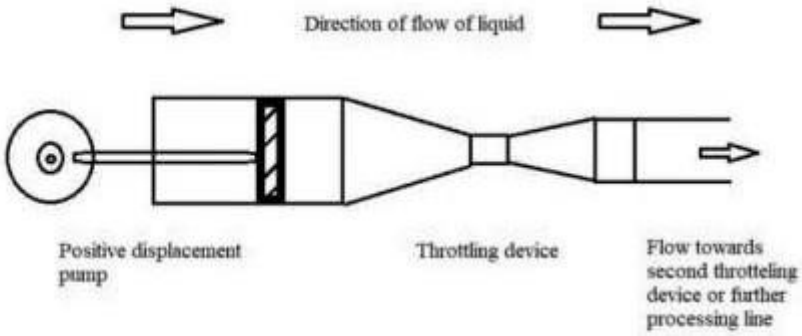
Various reactors have been developed to generate hydrodynamic cavitation, including liquid whistle reactors, high-pressure homogenizers, high-speed homogenizers, microfluidizers, orifice plates, and venturi systems. Each reactor utilizes a unique cavitation mechanism, offering specific advantages and limitations. The liquid whistle reactor generates cavitation through vibrating slits (Fig. 2.4). As the liquid flows through these slits at high speed, the movement causes the slits to vibrate, which then resonates with the liquid, creating cavitation effects. However, this reactor type has several drawbacks, such as limited flexibility, high wear and tear, significant energy consumption for pumping, low power output, and the inability to optimize the blade/slit movement frequency due to a lack of control. As a result, it is rarely used in food applications (Gogate, 2011).



(Source: Gogate, 2011)

Fig. 2.4 Liquid whistle reactor

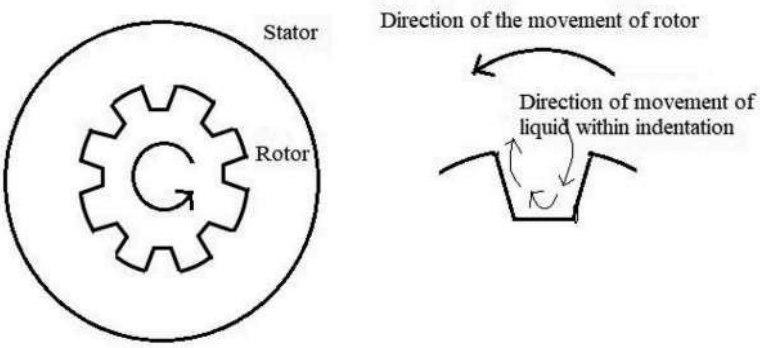
High-pressure homogenization operates by forcing liquid through a restrictive passage (Fig. 2.5) and is primarily used to modify the physiological properties of food products, such as reducing droplet size or facilitating emulsification. However, this method has certain limitations, including limited control over the reacting volume and cavitation intensity.



(Source: Gogate, 2011)

Fig. 2.5 High pressure homogenization

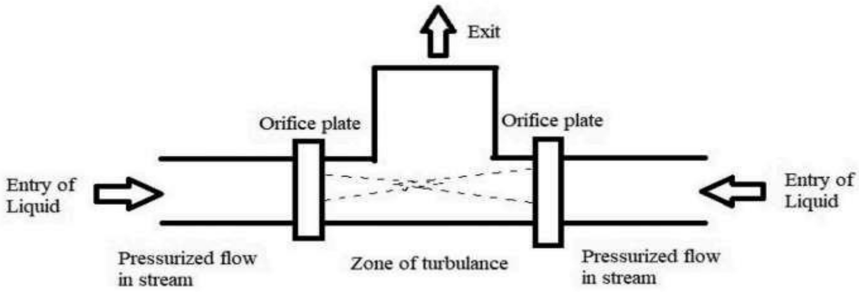
High-speed homogenizers are commonly used to treat various liquid products, such as emulsions of oil in water. These systems feature a rotor and stator, with the rotor equipped with small blades or indentations. As the liquid exits the rotor, local pressure drops below the critical pressure required for cavitation, causing the formation of cavities (Fig.2.6). The primary drawback identified by researchers is the significantly higher energy consumption (Fig.2.5) (Lohani *et al.,* 2016).



(Source: Lohani *et al.,* 2016)

Fig.2.6. Schematic of section of hydrodynamic cavitation and schematic for movement of liquid flow in indentations

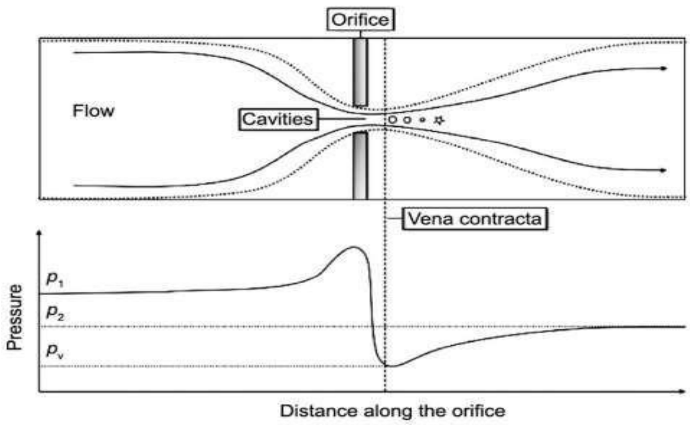
Microfluidizers operate by directing two high-pressure jets towards each other through orifices, where the turbulence generated within the flow causes mixing and cavitation. The high pressure and velocity of the liquid also lead to heating, which must be managed with an appropriate cooling system (Fig.2.7) (Loraine *et al.,* 2012).



(Source: Loraine *et al.,* 2012)

Fig. 2.7 Microfluidizer

The orifice plate or venturi setup is placed within the liquid flow path. This method of generating hydrodynamic cavitation has gained attention from researchers due to its ease of scaling up and its existing use in various industrial applications. Microfluidizers are considered to offer the highest flexibility and efficiency compared to other types of reactors used for hydrodynamic cavitation (Albanese *et al.,* 2017). An orifice plate is a widely used device for pressure reduction and flow restriction, featuring a borehole designed to create a specific pressurized flow. The sudden change in pipe diameter at the orifice leads to a significant intensity of bubble collapse.

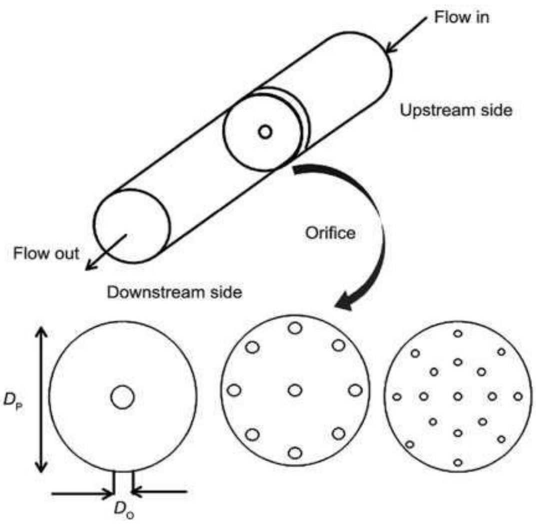


(Source: Albanese *et al.,* 2017)

Fig.2.8 Illustration of an orifice plate with a pressure profile

Bubbles form at the edge of the orifice, and to enhance this effect, multiple orifice plates have been designed. As the liquid passes through, boundary layer separation occurs, resulting in a substantial energy loss in the form of a permanent pressure drop. The magnitude of this pressure drop strongly impacts the intensity of turbulence at the downstream of constriction, and it is primarily determined by the geometry of the orifice and the flow conditions. A typical pressure profile for an orifice plate cavitation device is shown in (Fig.2.8), where p_1 is the upstream pressure, p_2 is the downstream pressure after recovery, and p_v is the vapor pressure of the fluid.

The diameter of the constriction is a crucial factor in orifice design and can have a significant impact on cavitation generation. An example is shown in Fig.2.9 (Carpenter *et al.,* 2017). Yan and Thorpe (1990) investigated both experimental and theoretical aspects of flow regime transitions caused by cavitation, where water passed through orifices of different sizes. They found that the cavitation number increased approximately linearly as the orifice diameter grew. Additionally, the collapse pressure generated by a single cavity was observed to rise with an increase in the orifice diameter. In their study of the orifice plate cavitation mechanism and its influencing factors using a numerical model, they discovered that cavitation induced by the orifice plate was closely related to the distribution of gas nuclei and the contraction ratio. The larger the contraction ratio, the greater the cavitation intensity.



(Source: Carpenter *et al.,* 2016)

Fig. 2.9 Illustration of a different orifice design

The flow area refers to the total cross-sectional area available for liquid flow within a cavitating device and is directly related to cavitation intensity. In a study optimizing hydrodynamic cavitation using salicylic acid, it was found that the concentration of free radicals was inversely correlated with the flow area. This indicates that cavitation intensity decreases as the flow area increases. Consistent with this, simulations showed that enlarging the flow area of the orifice resulted in lower fluid velocity at the constriction, slower pressure recovery and a higher cavitation number.

Venturi tubes have been widely studied and used for producing microbubbles in cavitation processes. A typical venturi tube consists of three sections: the converging inlet, throat, and divergent cone. Unlike orifice plates, the fluid within a venturi tube undergoes smooth contraction and expansion, causing gradual changes in fluid pressure and velocity. This smooth variation helps to avoid sudden pressure drops, which is advantageous for generating stable microbubbles. Due to their lower energy consumption and superior bubble generation capacity, venturis are preferred over orifice plates in many industrial applications (Saharan *et al.,* 2013).

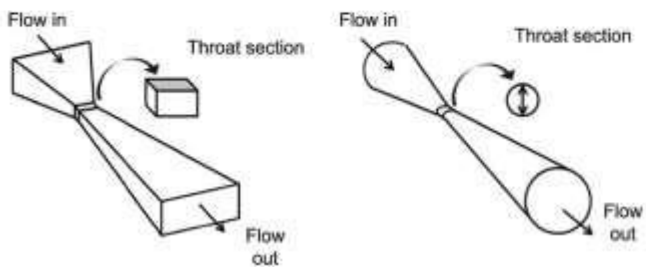


Fig. 2.10 Illustration of the geometric design of different venturis

The throat is a crucial part of a venturi, as it is where the bubbles are generated. The length of the throat is an important structural factor that affects its cavitation efficiency. Ashrafizadeh *et al.,* (2015) investigated the effect of different throat lengths (1.0, 1.5, 2.0, and 2.5 mm) on cavity formation. Their findings showed that increasing the throat length from 1.0 to 2.5 mm reduced the number of cavities generated, although energy dissipation due to friction increased. Saharan *et al.,* (2013) examined the impact of throat perimeter on the effectiveness of dye degradation using two types of venturis. They found that a slit venturi was more effective, yielding a higher degradation percentage than a circular venturi.

2.7 APPLICATION OF HC IN FOOD INDUSTRY

Microbial cell destruction Microbial cell disruption is a crucial application of hydrodynamic cavitation, which facilitates the release of intracellular components from microorganisms. The studies revealed that among the various technologies employed for microbial cell disruption, HC emerged as the most energy efficient option (Mevada *et al.,* 2019).

The studies conducted revealed an increase in the yield of lipids in wet micro algae when treated with hydrodynamic cavitation. This method was reported as a highly energy-efficient technique for extracting oil from algae. (Lee and Han 2015).

Recent studies conducted on hydrodynamic cavitation revealed the disruption of a significant quantity of MS2 viruses in large wastewater reservoirs (Kosel *et al.,* 2017). Scientist reported increase in cell rupturing and enzyme release with the number of passes and time of treatment while studying the effect of HC on baker's yeast (Save *et al*., 1994). The cavitation created by micro jets and shockwaves disrupts pathogenic microorganisms (Dong and Qin 2018). The studies demonstrated that energy efficiency increased by up to 63.19 times and the selective release of intracellular enzymes increased by up to 4.79 times when HC was used. (Mevada *et al.,* 2019). Balasundaram and Harrison investigated the impact of hydrodynamic cavitation on the disruption of E. coli cells by analysing the release of proteins from both the periplasmic and cytoplasmic compartments.

The maximum extent of protein release was observed at cavitation number 0.17, which falls within the range of cavitation numbers 0.13 to 0.92. They discovered that the cavitation number of 0.13 is the highest for optimal cell disruption, while the cavitation number ranges from 0.09 to 0.99. Studies were conducted on the effect of the geometry of the system and orifice number on periplasmic protein selective release using square, rectangular and circular holes. The results indicated that the amount of total soluble protein released was directly proportional to the hole area.

The release of acid phosphate was more pronounced in circular holes. The effect of flow rate was also studied after 1000 passes, which revealed that the release percentage is higher for the higher flow rate. (Balasundaram and Harrison 2011). From the reports above, we can conclude that HC is an effective method for cell destruction.

Hydrodynamic cavitation induces cellular inactivation by generating physical stresses within the cells. HC can be applied alone or in combination with thermal methods to sterilize food products. The primary benefits of certain methods utilizing HC include reduced energy consumption, effective microbial inactivation at lower temperatures, and preservation of food freshness. Research on fluid foods such as tomato juice, apple juice, and skim milk has demonstrated the ability of HC to eliminate bacteria, yeast, yeast ascospores, and heat-resistant bacterial spores (Milly *et al.,* 2008). Common spoilage organisms, such as yeast and lactic acid bacteria, can be inactivated at low temperatures through the combined effects of temperature and HC. Hydrodynamic cavitation lowers the sterilization temperature, resulting in products of higher quality. Hydrodynamic cavitation is more energy-efficient than pulsed electric field technology, allowing fruit juice industries to improve their efficiency by harnessing its effects. This study also indicated that scaling up the equipment is straightforward, making it suitable for large-scale industries with enhanced energy efficiency (Milly *et al.,* 2008). De Bonis and Ruocco (2010) noted that direct steam injection can also lead to the formation of hydrodynamic cavitation if the injection parameters are properly controlled.

Various physical and chemical methods are employed for water disinfection, including chlorination, flocculation, and UV treatment. However, since these methods are not 100% effective, researchers are exploring alternative techniques that offer greater efficiency. Research on disinfecting bore well water using hydrodynamic cavitation reactors such as high-speed homogenizers, high-pressure homogenizers, and orifice plate setups compared their effectiveness to acoustic cavitation from an ultrasonic horn-type reactor operating at 2 kHz and a power rating of 240W. The findings indicated that disinfection improves with an increase in the energy supplied to the system. Increasing the pressure in the orifice plate reactor setup with a 75 L capacity enhances the disinfection rate. This study demonstrated that cavitation is an efficient and time-saving disinfection method. Comparison studies evaluating disinfection per unit of energy consumed in all the equipment indicated that the high operating pressure orifice plate setup is more efficient than other cavitation reactors. The levels of disinfection achieved for the orifice plate setup, ultrasonic horn, and high-pressure homogenizer are 310, 45, and 5 CFU/J, respectively. The disinfection rate is higher for high-pressure homogenizers; however, their energy efficiency is lower, at only 5 CFU/J (Jyoti and Pandit, 2001).

Research by Arrojo *et al*., (2008) demonstrated the impact of cavitation designs and various operational parameters on the rate of E. coli inactivation. Three distinct configurations with the same overall free cross-section but varying numbers of holes. The study utilized one hole with a 5 mm diameter, six holes with a 2 mm diameter, and 25 holes with a 1 mm diameter. A venturi tube was also employed in this research. Mechanical disruption of bacteria occurred with slow pressure oscillations, specifically at low frequencies. Disinfection rates were highest in configurations and conditions that favour large bubble formation, prolonged pressure oscillations, and a greater number of cavitation events. These conditions were demonstrated by venturi tubes, which allowed for greater disinfection efficacy. (Arrojo *et al*., 2008).

The study examined the effects of various cavitation methods, including acoustic and hydrodynamic, alongside chemical methods like hydrogen peroxide and ozone for treating bore well water. It found that the destruction of HPC bacteria is enhanced when chemical methods are combined with ultrasonication. The disinfection of HPC was greater when hydrodynamic cavitation was combined with chemical methods, compared to treatment with hydrodynamic cavitation alone. The rate of cell disruption can be further enhanced by combining the HC reactor with hydrogen peroxide and an ultrasonic flow cell. The generation of free radicals, along with the individual effects of hydrogen peroxide, ultrasonic cavitation, and hydrodynamic cavitation, contributed to improved outcomes (Save *et al.,* 1994).

Studies were conducted on water treatment using liquid whistle hydrodynamic cavitation combined with ozone treatment. A suspension of E. coli was utilized to assess the treatment's effectiveness. Hydrodynamic cavitation achieved 2% disinfection, while the combination with ozone resulted in 75% disinfection. Although hydrodynamic cavitation has a limited disinfection capacity, ozone treatment is expensive. Thus, using a combined method serves as a good alternative to individual treatments (Sawant *et al*., 2008).

Proteins are essential nutrients for the human body, serving as the building blocks of tissues and also functioning as a fuel source. Experiments have been conducted on the hydrodynamic cavitation of both plant-based and animal-based proteins. Research was conducted to solubilize myofibrillar proteins found in chicken breast using a high-pressure homogenizer. Pressures of 0.1, 69, 103, and 168 MPa were applied for two passes to generate cavitation. After treatment, the solubility, particle properties, and microstructure of myofibrillar protein were evaluated. The results indicated that high-pressure homogenization decreased particle size and created an aqueous suspension of myofibrillar protein with a high absolute zeta potential. The decrease in size and increased intermolecular repulsion led to enhanced solubility of chicken breast myofibrillar protein. Therefore, high-pressure homogenization was determined to be an effective method for solubilizing myofibrillar proteins (Chen *et al.,* 2016).

Xu and Zhou continued their research on myofibrillar protein powder to enhance its functional properties, noting that structural changes can lead to improvements in these properties. A high-pressure homogenizer combined with hydrogen peroxide can be utilized to enhance the thermal stability of myofibrillar protein (Chen *et al.,* 2019). Research was conducted to examine the effects of High-Intensity Ultrasound (HIU), High-Pressure Processing (HPP), and High-Pressure Homogenization (HPH) on the physicochemical and functional properties of myofibrillar protein suspension, comparing the results with those of an untreated control sample. The results indicated that the sample treated with HPP exhibited increased solubility, while the sample treated with HPH showed reduced solubility. Rheological studies of the water treatment samples revealed that HPH had a lower ability to form gels compared to HP and HIU. Based on these findings, they concluded that HP is a good and effective method for producing gel-based meat products (Xue *et al.,* 2018).

Studies conducted on Lentil Protein Isolate (LPI) suspension indicated that High-Pressure Homogenization (HPH) is an effective method for altering the structural, functional, and rheological properties of LPI suspension. However, the results revealed that HPH treatment does not affect the protein pattern. Particle size decreased up to 100 MPa, with size distribution becoming mono-modal after 50 MPa. As the pressure increased from 50 to 150 MPa, protein unfolding occurred, as observed in the microstructural images. The unfolding of protein particles aligns with the findings related to water solubility, foaming, emulsifying properties, and particle size. LPI behaves as a shear-thinning fluid, and the results adhered to the Ostwald de Waele model. Apparent viscosity was represented by an exponential function, while homogenization pressure followed a sigmoid function. Homogenization pressures exceeding 50 MPa, after 51.78°C, demonstrated enhanced gelation capacity. (Saricaoglu, 2020).

Studies on Soybean Protein Isolate (SPI) emulsion gels revealed that high-pressure homogenization positively affects gelling and rheological properties, showing that the strength of SPI emulsion gels increases with higher HPH pressure. The water holding capacity of the emulsion gel improved as the pressure increased from 5 to 20 MPa, rising from 87.7% at 5 MPa to 91.4% at 20 MPa. However, further increasing the pressure to 80 MPa did not impact the water holding capacity. The microscopic fractal dimension of SPI emulsion gel ranged from 2.96 to 2.99. Increasing the pressure of HPH on the emulsion resulted in a more stable isotropic network gel structure (Bi *et al.,* 2020).

Studies were conducted to enhance the functional properties of freeze-dried myofibrillar protein powder by modifying its structure through High-Pressure Homogenization (HPH). The homogenization intensity applied in this study ranged from 0 to 20,000 psi. The dissociation of myosin and myofibrillar polymers was observed in water-soluble myofibrillar protein powder (WSMP-P) following HPH treatment. HPH also led to the dissociation of myofibrils and myosin, as well as the formation of actin trimers through partial unfolding and rearrangement, thereby altering the structure of WSMP-P. This dissociation and the formation of actin trimers resulted in an amorphous protein structure with enhanced thermal stability. The results demonstrated that HPH can enhance the water solubility and emulsifying properties of WSMP-P by reducing particle size to an unfolded structure at the submicron level and generating a high surface net charge in aqueous suspension (Chen *et al.,* 2017). This study suggests that WSMP-P could be used as a protein supplement in food and beverages under low ionic conditions. Myofibrillar proteins (MPs) account for 50% of total meat and are only sparingly soluble in low ionic strength solutions or water. Complete solubilization of myofibrillar proteins can be achieved with high salt concentrations. Investigations into the solubility of myofibrillar proteins in low ionic solutions using 15,000 psi High-Pressure Homogenization (HPH) concluded that HPH caused the unfolding of MPs. This unfolding exposed hydrophobic and sulfhydryl groups, leading to the formation of myosin oligomers through disulfide bond formation. The alteration in myosin conformation hindered film formation while simultaneously enhancing the solubility of the MPs in water (Chen *et al.,* 2016).

Studies were conducted on lactase treated α-lactalbumin (α-LA) that had been pretreated with high pressure homogenization (HPH) to investigate the effects of HPH on its physicochemical, structural, and functional properties. Pressures of 20, 40, 60, 80, 100, and 120 MPa were applied for four cycles to the laccase-treated α-LA. The number of lactase treated α-lactalbumin decreased with increasing pressure, while the levels of oligomers and polymers rose. FTIR spectroscopy results indicated an increase in random coil content and a decrease in α-helix as homogenization pressure increased. Additionally, the degree of cross-linking, emulsifying properties, functionality, and gel forming capabilities improved with HPH pretreatment (Ma *et al.,* 2023).

Impact of the geometry of the disruption chamber on myofibrillar protein was investigated and found that passing through a narrow nozzle in a counterflow pattern resulted in a decrease in myofibrillar particle size. Cavitation generated in the narrow nozzle with a counter-flow pattern facilitated the disruption of the secondary structure of myofibrillar protein in water. This disruption exposed hydrophobic groups and sulfhydryl (SH) groups, enhancing the solubility and stability of the myofibrillar protein solution. High-Pressure Homogenization (HPH) was the method used to create this cavitation (Li *et al.,* 2019).

Research on soy protein isolate compared the effects of hydrodynamic cavitation (using a venturi tube) with ultrasonic cavitation on its functional and physicochemical properties. The analysis included its electrophoretic profile, pH, particle size, viscosity, surface hydrophobicity, sulfhydryl content, protein solubility, emulsifying properties, and foaming properties. The results indicated that hydrodynamic cavitation outperformed ultrasound when treating 2 L of soy protein isolate. However, when a 20 ml volume was treated with both methods, they exhibited similar properties. This suggests that hydrodynamic cavitation is more suitable for processing larger quantities of food. (Li *et al.,* 2020). Research on an edible film made from mechanically deboned chicken meat protein after HPH treatment at pressures of 0, 25, 50, 75, 100, and 150 MPa showed that particle size decreased up to 10 MPa, resulting in good water vapor permeability and enhanced tensile strength for the film. However, 150 MPa did not yield a smooth and homogeneous surface in the micrograph. Pressures up to 100 MPa can be applied to the film suspensions to produce films with improved barrier and mechanical properties (Saricaoglu, 2020).

In the emulsification process, two or more immiscible liquids combine to create a semi-stable mixture. In food applications, these typically consist of an organic (oil) phase and an aqueous (water) phase, which are stabilized by the addition of a food-grade emulsifier (surfactant). Emulsifiers are employed to stabilize emulsions. High-Pressure Homogenization (HPH) is an effective method for producing stable emulsions, enhancing their texture and resulting in a finer consistency. A study examining the effect of high-pressure homogenization on oil-in-water emulsions stabilized with Muscle Myofibrillar Protein (MMP) demonstrated improved properties, including an increase in the emulsifying stability index (from 59.33 to 154.62 minutes), emulsifying activity index (from 56.93 to 87.68 mg), and apparent viscosity. The absolute zeta potential increased from 10.67 to 37.03 mV. The droplet size of the emulsion was reduced from 39.5 µm to 0.46 µm. The results also indicated a decrease in the cream index value, while the solubility of the emulsion rose to 75.1% from 16.5%. The research concluded that the changes observed in the emulsion may be attributed to the increased solubility and exposure of hydrophobic groups (increased from 196.37 to 258.50). Pressures of 40, 80, and 120 MPa were applied to assess the effects, with 80 MPa yielding the finest and most stable emulsion (Cha *et al.,* 2019). These results shed light on the potential of natural emulsifiers. Studies indicated that MMP can serve as a natural emulsifier in food, and they also provided a method to enhance the formulation and properties of the emulsion.

Zhang *et al.,* (2016) investigated the effect of hydrodynamic cavitation on emulsification, using refined soybean oil as the oil phase. A valve with a 3 mm diameter was employed to generate hydrodynamic cavitation, with the inlet pressure regulated by adjusting the valve opening. To examine the effect of inlet pressure, a series of emulsions were prepared by varying the inlet pressure. Emulsions were created at pressures of 20, 50, 80, 100, 120, and 150 psi. A decrease in droplet size was observed as the pressure increased from 20 to 120 psi, with the size remaining constant after reaching 120 psi. A particle size of 27 nm was achieved at 120 psi. The negative zeta potential and a polydispersity index of less than 0.1, observed after 120 psi, indicated the monodispersity of the emulsion. The oil-in-water emulsion produced by hydrodynamic cavitation remained stable for up to 8 months. These findings highlight the potential of hydrodynamic cavitation for emulsification (He *et al.,* 2016).

The study by Carpenter *et al.*, (2017) on the influence of geometry and geometrical parameters on the formation and stability of mustard oil-in-water emulsions reported a droplet size of 87 nm achieved using a circular orifice plate with a single hole. This orifice device had a smaller perimeter and a larger flow area compared to other reactors, such as venturi tubes and different orifice configurations. The smallest droplet size represented the optimal condition for device optimization, achieved at a cavitation number of 0.19 after a processing time of 90 minutes. The mustard oil-in-water nano-emulsion produced by hydrodynamic cavitation remained kinetically stable for up to 3 months under both centrifugal and thermal stress conditions. Hydrodynamic cavitation was found to be 1.5 times more energy efficient than acoustic cavitation (Carpenter *et al.,* 2017). The orifice plate with a 0.0010 cm hole diameter, used in a liquid whistle hydrodynamic cavitation reactor, generated a submicron emulsion with a droplet size of 476 nm when the inlet pressure and the distance between the blade and the orifice were optimized. (Parthasarathy *et al.,* 2013).

The food and beverage industries apply the principle of hydrodynamic cavitation for various operations, including homogenization, pasteurization, and the breaking or mixing of food macromolecules. The use of hydrodynamic cavitation has proven advantageous due to its higher energy densities and efficiency in microbial disinfection and extraction processes. The impact of hydrodynamic cavitation on beer brewing powder was investigated and found that it enhanced starch extraction efficiency compared to traditional methods. Additionally, under moderate hydrodynamic cavitation, the saccharification temperature decreased to 35 °C, improving energy efficiency by approximately 30%. The treatment also resulted in a reduction in gluten concentration without compromising the original flavour, taste, or aroma (Albanese *et al.,* 2017).

The use of high-pressure homogenization (HPH) to reduce the consistency of concentrated orange juice was studied by applying pressures up to 150 MPa. The results demonstrated the benefits of HPH, with the flow behaviour index increasing to 1% at 10 °C, and a reduction in product consistency by 64% along with a 50% decrease in viscosity. This reduction contributes to lower energy consumption during pumping, ultimately benefiting the industry's profitability (Leite *et al.,* 2014).

Researchers studied the effects of high-pressure homogenization (HPH) on carrot juice, focusing on stability, water-soluble pectin, and the bioavailability of total carotenoids. They investigated various process parameters, including the number of passes (1, 2, and 3), pressures (20, 60, 100, 150, and 180 MPa), and inlet temperatures (25, 50, and 70 °C). The results demonstrated an improvement in the stability and total carotenoid bioavailability of carrot juice, along with alterations in the characteristics of water-soluble pectin in homogenized carrot juice. However, variations in parameters did not significantly affect uric acid content, degree of methylation, or acetylation. Overall, the findings indicate that the application of high-pressure homogenization can modify pectin characteristics and enhance the total carotenoid content of carrot juice (Zaaboul *et al.,* 2019).

Research on the effect of high-pressure homogenization (HPH) on microbial inactivation and quality attributes such as antioxidant capacity, bioactive components, and physicochemical properties of mango juice treated at moderate inlet pressures (40-190 MPa) and temperatures (20-60 °C) reported complete microbial inactivation. The processed juice remained stable without microbial contamination for up to 60 days, with no adverse effects on its physicochemical characteristics or bioactive components. Additionally, the treatment improved levels of carotenoids, ascorbic acid, and total phenols (Chen *et al.,* 2017). The literature review indicates that Wine, as a fermented beverage, offers significant nutritional value, and hydrodynamic cavitation holds promise for producing high-quality wine. Some studies on hydrodynamic cavitation have shown results comparable to ultrasound processing. However, no research has been conducted specifically on the hydrodynamic cavitation of wine. The feasibility of this approach can be justified, as hydrodynamic cavitation could effectively enhance the quality parameters of wine in a manner similar to ultrasound.