Micronisation and Nanosizing of particles for an Enhanced Quality of Food: a Review

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ABSTRACT

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Size reduction to micron to nano-size range is rapidly developing technology applied to foods in the recent decades. This article reviews the particle size reducing technologies for solid particulate and liquid materials. For solid particulate materials, the jet milling, ball milling and colloid milling are mainly used. For liquid materials, primarily the high pressure homogenization, ultrasonic homogenization and microfluidisation technologies are used. Due to the reduction in particle size, micron- and nanotechnology significantly enhance the physico-chemical and functional characteristics of food materials, resulting in the improvement of food quality.

Keywords grinding homogenization food quality

INTRODUCTION

Micron- and nanotechnology are rapidly developing technologies which involve reducing the particle size by mechanical or hydrodynamic methods to overcome the internal cohesion and cause the breakage of materials. With the decrease of particle size, the characteristics of materials can undergo some changes which crude particles do not possess, such as surface effects, macro quantum channel effects, quantum effects and optical, mechanical, magnetic, chemical and catalytic properties (Huang et al., 2008a). Due to these notable changes, ultrafine powders are applied to various fields, including ceramics, electric materials, pharmaceutics, chemicals and papermaking and so on (Ogawa et al., 2003; Masciangioli and Zhang, 2003; Soppimath et al., 2001; Rasenack and Muller, 2004). It is also an effective method to grind the biomaterials into superfine particulates for efficient extraction of active compounds. Over the past few years, many unit-operations have been developed in biological powder technology with the rapid and steady development of micro- and nanotechnologies. In the meantime, micro- and nano-technologies have attracted much attention in food industries, and become the focus of research in many countries(Sanguansri and Augustin, 2006).

Comparing with traditional comminution methods, micron- and nanotechnologies possess many advantages. Firstly, a smaller size means a larger surface area, resulting in improved water absorption, high solubility, flavour release, and a soft mouthfeel. Riley et al. (2008) found that superfine powders of yam (*Dioscorea* sp.) starch were fluid, soluble, and possessed good water holding capacity (WHC). In addition, the solubility of nutritive components due to the reduction

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in size by superfine grinding increases and are also easily absorbed by the human body. The bioavailability of B vitamins (niacin, pantothenic acid and thiamin) to humans was higher by finely grounding bran as compared to the coarser corn bran (Yu and Kies, 1993). Due to the large specific surface area of fine particles, the reaction rate of product is effectively increased in the biological and chemical reactions. For example, corn bran with a finer particle size was more easily fermented than bran with a coarser particle size (Ebihara and Nakamoto, 2001). The reduced size of superfine ground rice straw powder promoted the enzymatic hydrolysis (Jin and Chen, 2006). The concentrations of short-chain fatty acids in small-particle bran were found greater than in large-particle bran. The reason was likely that bacterial enzymes had a larger contact area to access fermentable carbohydrates (Stewart and Slavin, 2009; Jenkins et al., 1999). The materials containing high amounts of fiber, conventional crushing method cannot fully grind it, resulting in enormous waste. When the particle sizes of insoluble fiber fraction of Liucheng sweet orange was reduced to micron-size by different micronization technologies, their functionalities were enhanced and the activities of α-amylase and pancreatic lipase were retarded (Chau et al., 2006b). Micron- and nanotechnology can be applied to grind food at low temperature and in short time to keep the active ingredients of the materials intact, ensuring the high quality product. For example, Murthy and Bhattacharya (2008) found that the loss of volatile from oil black pepper prepared by ambient grinding was about 50% as compared to cryogenic grinding. In their work, cryogenic grinding technique was also found superior to other grinding methods in terms of monoterpenes retention in the powder.

This article is aimed at reviewing the effect of particle size reduction by applying micron- and nano-technologies on food functionalities and quality. The size reduction to an appropriate

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level can modify or enhance the physico-chemical and functional characteristics of food materials. This review will mainly cover the size-reduction technologies such as: jet milling, ball milling and colloid milling, high pressure homogenization, ultrasonic homogenization and microfluidisation. The detailed introduction and comparison of different methods are shown in Table 1.

Size reduction of solid particulate materials

Jet milling

Jet mill, also known as airflow grinding, is a fluid energy impact-milling technique which is commonly used to produce particle sizes of less than 10 μm (Palaniandy et al., 2009; Palaniandy et al., 2008). The feed particles and compressed gas or superheated steam are injected into a mixing chamber where the inflow of the gas promotes breakage by causing particle to particle and particle to wall collisions(Djokic et al., 2014). As it is not possible to classify particles during the milling process, an air classification system is typically added externally that sifts the end product into coarse and fine materials. The coarse particles are recycled back into the system and the fine ones proceed to the next unit operation (Kastner et al., 2013). Gommeren et al. (2000) illustrated a simple jet milling schematic diagram which can be seen in Fig. 1. Compared with the ordinary superfine disintegrator, jet mill can produce a very finely ground product without the risk of contamination due to an autogenous grinding mechanism, low wear rate, and small footprint, which also leads to a reduction in the space requirements, low noise and the ability of grinding heat-sensitive materials (Berthiaux et al., 1999; Midoux et al., 1999; Muller et al., 1996). Therefore, this method is used in the chemicals, pharmaceuticals and minerals

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(Midoux et al., 1999). The application in food particulate grinding such as protein powders is also reported (Hayakawa et al., 1993). The energy consumption of jet milling is generally several times higher than other grinding methods. Due to the high cost, low yield and low energy utilization rate, the development of jet milling is limited. Therefore, strengthening of theoretical study and finding an effective way to improve the design of the equipment are required.

Ball milling

Ball milling is a low-cost and environmentally friendly mechanical method to crush solid materials. The comminution of granules is due to intensive milling force, in conjunction with the pressure and friction action of the ball (Zhang et al., 2010). Due to these actions the particles can fracture and localized heating/melting can occur resulting into amorphorization of crystalline materials. One type of ball mill which is a versatile device for efficient grinding is the planetary ball mill. It consists of two or more jars installed on a disk, rotating at an angular velocity ω around their axis (Fig.2). The impact of the milling media (balls and jars) on the particulate materials results in reduction of their particle size, which is due to centrifugal and Coriolis forces. The energy available for comminution to reduce the size of the material is determined by several parameters, such as friction coefficients, angular velocities, grinding time (Broseghini et al., 2015). The application of ball milling has been extended to many materials, such as powder-like components of energetic materials (Ren et al., 2010; van der Heijden and Leeuwenburgh, 2009),

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artificial bone compositions (Zahrani and Fathi, 2009), advanced mechanically alloyed powders (Suryanarayana, 2008; Zhang, 2004), composites (Esawi and Morsi, 2007) and low-dimensional structures (Li et al., 2011; Fan et al., 2010; Chen et al., 1999).

Ball milling is also increasingly being applied to grind the food materials. Ball milling treatment caused phase transition from crystalline to glassy state of semi-crystalline starch granules and also induce transition of glassy to rubbery state of potato starch (Kim et al., 2001). Zhang et al. (2014) found that the antioxidant activitiy of Lycium barbarum polysaccharides was enhanced by size reduction by ball milling. Compared with native starch, the apparent viscosity and gelatinization temperature of ball milled cassava and maize starch decreased due to partial destruction of crystalline structure while the cold-water solubility and transparency increased (Huang et al., 2008b; Huang et al., 2007). The change in terms of physico-chemical properties was also demonstrated by Zhang et al. (2009), who found that the angle of repose and swelling capacity of Chaenomeles sinensis (Thouin) Koehne fruit powder were improved after ball milling treatment. Due to the destruction of crystalline structure of starch granules and modification of gelatinization property, jicama and cassava starches grinded by ball-mill showed its potential to be used as stabilizer, moisture retainer and thickener (Martinez-Bustos et al., 2007). Ball-milling treatment of tuber crops, including yam (*Dioscorea alata* L.), taro (*Colocasia esculenta* L.) and sweet potato (*Ipomea batatas*L.) resulted in the redistribution of fiber components from insoluble fiber to soluble fiber and increased their solubility (Huang et al., 2010).

Colloid mill

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A colloid mill is mainly composed of a stator and a rotor. There is a small gap between them. When the materials pass through the space, the rotor rotates at a very high speed. The materials adhering on the rotating surface will have a maximum speed, while the materials on the stator relative to the rotor will be still. So there is a high velocity gradient between them, which results in the grinding by the strong shearing (see Fig.3) (Maindarkar et al., 2014). The viscous and dense material can be grinded into 2 ~ 50 μm in very short time and the mill also has mixing, emulsifying, homogenizing effects. The colloid mill has the advantages of simple structure, easy operation and space requirement. However, the gap between the stator and the rotor is small and the working area is large. Although the machining efficiency can be increased, the machine is easy to be worn. In addition, due to the structure of colloid mill, the processing capacity is very limited and the forced feeding device may be needed to ensure the smooth flow of materials.

Vishwanathan et al. (2011) used three different wet grinding systems to grind soybean. The results demonstrated that the colloid mill can generate the greater particle size reduction of soybean and specific energy consumption was only one-fourth of the mixer grinder and half of the stone grinder. In addition, the operations of the mixer grinder and the stone grinder were batch type while the colloid mill was suitable for continuous operation. Therefore, colloid mill is a potential device for industrial scale operation. Sharma et al. (2008) reported that colloid mill imparted smaller damage to starch granules compared to stone grinder which involved larger compressive force.

Changes in physico-chemical properties and functionalities during milling

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The particle size and crystal structure of the powder can be effectively modified after ultrafine grinding. At the same time, superfine grinding can lead the surface area and porosity of materials to be increased, so that the ultrafine powder can be produced with unique physical and chemical properties, such as good dispersion, adsorption, solubility, chemical activity, biological activity, etc.

The angle of repose (θ) is defined as the maximum angle subtended by the surface of a heap of powder against the plane which supports it. Angle of repose and slide are important indexes for the flow properties of powder. When the angle of repose and the sliding angle are bigger, the powder fluidity is worse, on the contrary, the lower values indicate better the fluidity of powder. Zhao et al. (2009) found that the angle of repose and slide values of ginger powder decreased and the flow property was enhanced with the decrease of the particle size. As the powders have more tendencies of surface interactions and aggregation characteristics, surface attachment would also be higher. Therefore, the quality of ginger powder would be more stable and the mixture would also be uniform and non-separable. Similar observation was reported for silver carp bone powder (Wu et al., 2012). The modification of particle size and geometrical structure of powder would also influence the hydration properties, such as water holding capacity, water solution index and swelling capacity. Zhao et al. (2009) found the fact that the water holding capacity of Astragalus membranaceus powders was increased. This is due to the fact that after micronization, the surface area and energy of powder will be increased. Moreover, by creating new surfaces hydrophilic groups in the cellulose and hemicelluloses of the particles might have been exposed more, which resulted in an easy integration with water that finally led to an increased water holding capacity (Zhao et al., 2010). Wang et al. (2009) also reported the increased swelling capacity of starch with the decrease in particle size. In addition, the dispersibility and solubility of superfine powder would also increase during rehydration.

Dietary fibers are classified as soluble and insoluble dietary fibers. Soluble dietary fibers have a good adsorption on metal ions in our body and can reduce blood cholesterol, regulate blood sugar, reduce the risk of heart disease and other functions. So many studies indicate that soluble dietary fiber is more important than insoluble dietary fiber in many health aspects (Galisteo et al., 2008; Vasanthan et al., 2002). Chau et al. (2007) have found a redistribution of fiber components from insoluble to soluble dietary fibers after ultrafine grinding. The decrease of insoluble dietary content is due to the degradation of hemicellulose, cellulose and lignin, which breakdown into some small molecular compounds(Zhu et al., 2010). Using this method is possible to produce high quality dietary fiber with improved functionality.

In another application, Li et al. (2012) produced fresh noodles from wheat flour added with superfine green tea powder. The result showed that superfine green tea powder could increase the stability, elastic modulus (G′) and viscous modulus (G″) of wheat dough. Furthermore, the right amount of superfine green tea powder also improved the scores in sensory evaluation of green tea noodles. With this wheat flour, calorie of cookies could be reduced with an increase in the acceptability for color, aroma and taste of cookies (Ahmad et al., 2015). Hao et al. (2008) also reported that alfalfa powder concentration and granularity could influence the dynamic rheological properties of alfalfa-wheat dough. Elasticity and viscosity of the alfalfa-wheat dough increased and the dough gelatinization temperature was lowered by the reduction in particle size.

The reduced size by grinding can also alter other functional properties of the food materials. Ultra-fine powders of cinnamon and clove obtained by a ball mill were found to have an increased effect to inhibit the growth of spoilage organisms from meat (Xuan et al., 2011). In theory, the releasing rates of active ingredients of powders are proportional to its specific surface area. That is, the smaller the sample particle is, the faster the active ingredient releases. So the inhibitory activities of cinnamon and clove powders increased with the decrease of particle size. Similar effect of micronisation was reported for insoluble fiber prepared from the pomace of *Averrhoa carambol (Hsu et al., 2007)*. The micronization treatment could increase the inhibitory and bactericidal activities of the fiber by 2–8 fold and 2–4 fold, respectively. To enhance the utilization of persimmon peels as bio-resources, physicochemical properties and antioxidant activities of the powders with various particle sizes were investigated by Hwang (2011). It was found that contents of extractable antioxidants (total phenols and total flavonoids) increased inversely to the particle sizes of the powders. The most likely reason was that the micronization altered or destroyed the dietary fiber matrix, thus making some antioxidative compounds released or exposed (Zhu et al., 2010). Similarly, Zhao et al. (2015) studied antioxidant activity of red grape pomace powders with various particle sizes (>300, 250–125, 125–70, 70–38, and < 18.83 μm). The extract of grape pomace powders with a particle size of < 18.83 μm showed the best antioxidant activity through all antioxidant assays. So, the increase in antioxidant property of commuted powder could be beneficial for improving the nutritive value of food. In another study, with micronization processing, the potential hypocholesterolemic activities of insoluble fibers prepared from carambola and orange pomace were found different. With micronization, the cation-exchange capacity of insoluble fibers was effectively increased and the abilities to

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lower the concentrations of serum triglyceride and serum total cholesterol were greatly improved, likely due to enhanced excretion of cholesterol and bile acids in feces (Wu et al., 2009). It was also reported that the adsorption capacity of okra powder for cholesterol increased with decreasing particle-size functionalising the okra powder as an effective cholesterol sorbent (Chen et al., 2015). Adding 2% micronized dietary fiber of orange by-products to yogurt, the physico-chemical and functional properties of products were also improved. Therefore, micronized dietary fiber could potentially be used as a fat replacer in low-fat yogurt, without sacrificing good taste and other qualities of full-fat yogurt (Yi et al., 2014).

Influence of different grinding methods on food quality and variation on functionality of powders

The physical and chemical properties of the powders determine the degree of their comprehensive utilization. However, the characteristics of the powder are closely related to the particle size and process. With different grinding methods, the properties of powder can be very different.

In a recent study, Meghwal and Goswami (2014) used rotor, ball, hammer and pin mills for the milling of the fenugreek and black pepper seeds, and compared the time required for grinding, overall power consumption, specific surface area created after grinding, moisture content before and after grinding and color change. The results showed that rotor mill was found to be the best way for grinding fenugreek and black pepper spices. By comparing the effects of cryogenic grinding and hammer milling on the flavour attributes of black, white, and green pepper, Liu et al. (2013) also found that cryogenic grinding was better than hammer milling for preserving the sensory properties and flavour attributes of pepper without significantly affecting its quality. Chau et al. (2006a) investigated the effects of ball milling, jet milling and high-pressure micronization on the characteristics and functional properties of carrot insoluble fiber-rich fraction. The results demonstrated that the high-pressure micronization could significantly increase the chemical properties, glucose adsorption capacity, a-amylase inhibitory activity and pancreatic lipase inhibitory activity of the insoluble fiber-rich fraction. The result was similar with the micronization of orange insoluble fiber fraction (IFF) that compared unmicronized IFF, jet-milled IFF, and high-pressure micronized IFF and the later was found to produce the best product (Wu et al., 2007). Marin evaluated superfine powder of wheat bran grinded by different laboratory and pilot scale technologies. Optimum results were achieved by a combination of ball milling followed by treatment of the powder with a jet air mill (Marin and Deleu, 2014).

Size reduction in liquid materials

High pressure homogenization

High pressure homogenization is used in several areas, such as chemical, pharmaceutical and biotechnology and food industries. Homogenization pressures normally used in the industry are between 20 and 50 MPa, but current development of homogenizers can reach much higher pressures. The principle of high pressure homogenization is that high pressure force the liquid material to flow through a narrow gap valve, which greatly increases its velocity, leading to high shear stress in the valve gap and depressurization. After the gap outlet, the flow kinetic energy is converted into turbulence and cavitation, as the jet breaks down and impacts in internal solid surfaces of the homogenizer (Dumay et al., 2013; Floury et al., 2004; Innings and Trägårdh, 2007). Thus the macromolecules and suspended particles in the fluid are subjected to great mechanical stress, becoming twisted, deformed and disrupted (Floury et al., 2004).

Homogenization is a special procedure in the production of homgenised milk, juice or vegetable based beverages. Homogenization has an effect on the particle size distribution, colour, cloudiness, flavonoid content of vegetable based beverages and the impact follows an asymptotic behavior. Betoret et al. (2009) found that homogenization pressure of 20 MPa or more, the quality of fresh fruit juice will be improved. The homogenization can decrease particle size with no negative impact on the colour of juice, as well as the total flavonoid content. Apart from the decreasing of particle size, high-pressure homogenization (HPH) could influence the water holding and swelling capacity, and rheological properties of orange pulp due to the inverse relation between the particle size and water holding capacity. HPH at 800 MPa resulted in a more homogeneous appearance, smoother suspension and increased the relative presence of water-extractable pectin (Van Buggenhout et al., 2015). But Silva et al. (2010) found that applying homogenization pressures above 400 MPa, sedimentation may occur in juice and the highest sedimentation index was observed for samples treated at 700 MPa, which was ascribed to

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the formation of aggregates due to interparticulate attraction. Therefore, a stable pineapple pulp with negligible phase separation could be produced within the pressure range from 10 to 30 MPa. In other work, because of the leakage of lycopene from the disrupted cells, HPH treatment caused the change of color of tomato juice (Kubo et al., 2013). Moreover, HPH increased the absolute zeta potential, lightness and total suspended solids of the homogenized sample. The effect of HPH on the microstructure of taro pulp can be seen in Fig.4, which showed these suspended particles were strongly broken down during HPH processing, increasing the consistency and stability of taro pulp (Yu et al., 2016). Compared with thermal pasteurization treatment, the ultra high pressure homogenization (UHPH) treatment could also retain more content of L-ascorbic acid and flavanone content in orange juice (Velázquez-Estrada et al., 2013).

For protein beverages, such as soymilk, homogenization can prevent fat floating and age thickening phenomenon. The digestibility and gloss of product are improved, along with taste and stability. For example, UHPH tremendously reduced soymilk microbial load and caused disruption of colloidal particles or aggregation of the components, especially at 300 MPa (Cruz et al., 2007). UHPH also significantly reduced the particle size of hazelnut milks, in which the particle size distribution turned from bimodal and poly-disperse to mono-disperse distributions. In addition, particle surface charge, clarity and Whiteness Index were also increased (Bernat et al., 2015). In some research, UHPH technology has been applied as an alternative to those thermal treatments. Compared with ultra high temperature, UHPH could produce the soymilk with stable levels of oxidation, high physical stability, no microbial growth and a positive trend of sensory response during the storage period (Poliseli-Scopel et al., 2014). The conversion of isoflavone forms to aglycones was higher of soymilk with ultra high temperature treatment than UHPH during storage. However, the lower percent of aglycones can better maintain the quality of proteins. In addition, UHPH samples showed a lesser amount of blocked lysine (Toro-Funes et al., 2014). The UHPH treatments could retain most of the vitamin content present in raw milk with higher nutritional value than heat-treated milk (Amador-Espejo et al., 2015).

High pressure homogeneous is also applied to make emulsions. For example, Fernández-Ávila et al. (2015) found the oil-in-water emulsions with UHPH became more stable with low particle size value, greater viscosity and partial protein denaturation. Similarly, the modifications in the structure and the texture of emulsions happened with the increasing homogenization pressure.

Ultrasonic homogenization

Ultrasonic homogenization is a process in which high intensity ultrasonic waves cause intense shear and pressure gradients to disrupt emulsion droplets. Such disruption of droplets is mainly attributed to the cavitation effect. Instead of forming a primary emulsion, ultrasonic homogenization is applicable to reduce the size of existing emulsions. The frequencies of ultrasonic homogenization are usually use range from 20 to 50 kHz.

Compared to conventional homogenization, ultrasound treatment is a very effective way to reduce the fat globule size. Wu et al. (2000) studied the effects of ultrasound on milk homogenization. They found that the exposure times and power levels of ultrasound would influence the effectiveness of homogenization. That is, efficient homogenization effect was not achieved at low power and extremely small fat globules will only be produced with enough power and exposure time. For example, Sfakianakis et al. (2015) found high intensity ultrasound homogenization reduced the fat globule size of milk to 0.78 μm. Similarly, Ertugay et al. (2004) found that the smallest fat globule diameter of milk was 0.725 μm at a power level 100%. Şengül et al. (2009) found that the water holding capacity of yogurt was improved with the increase of exposure times and amplitude levels. In another study, the effect of ultrasonic treatment on bacteria numbers of buffalo milk was investigated. The results showed that the logarithms of numbers of bacteria were decreased by the ultrasound treatment of milk (Al-Hilphy et al., 2013).

Microfluidisation

Microfluidization is a continuous, high-shear fluid process that uses high pressure to generate high velocity micro-streams, in which the fluids collide with each other and with the wall surface that cause the formation of fine emulsions within an interaction chamber (Mccrae, 1994). Compared with the other conventional homogenization techniques, microfluidization can cause the same degree of emulsification at lower pressures. In addition, the particle size of emulsion after microfluidization would be smaller and the size distribution would be narrower (Jafari et al., 2008). The technology has been investigated as an alternative method for emulsifying ranges of food products and also homogenizing milk and processing a range of milk based products, such as infant formulae, cheese and ice cream. Microfluidization can produce non-fat or low-fat ice creams that usually had a slower meltdown without affecting sensory properties (Olson et al., 2003). Compared with homogenized milks, the milks treated by microfluidizer contained smaller emulsion particles overall. There were fewer intact or semi-intact micelles forming on the membrane surface of the fat globule in the microfluidized milks (Dalgleish et al., 1996). The extent of fat separation of microfluidised milk was reduced significantly during storage (Hardham et al., 2000). The high pressure microfluidization could influence the microstructure of mozzarella cheese made from microfluidised milk, in which the fat globules were much smaller at the higher pressures (Tunick et al., 2000). Ciron et al. (2010)

found microfluidization could not only maintain the water retention of yoghurts, but also cause more interconnectivity in the protein networks with embedded fat globules. Also, the thickness, creaminess, cohesiveness and viscosity of the yoghurt could be improved by microfluidization of yoghurt milk. This technique findings can also be used to produce high-quality low-fat yoghurt (Ciron et al., 2011). (Augustin et al. (2008)) found that microfluidisation could improve the functionality of resistant starch with the increase of water retention and viscosity.

Conclusion

The article reviewed the particle size reducing technologies for solid and liquid particulate materials, including jet milling, ball milling, colloid milling, high pressure homogenization, ultrasonic homogenization and microfluidisation. The reduction of particle sizes of materials to micro-or nano-sizes would result on some changes in structure, surface area, physico-chemical and functional properties. This brings on some new applications in the food industry. Micron- and nano-technologies can have a wide range of application and features of simple operation. At the same time, the products can have high an added value and be profitable.

However, the solid micronization technology also has some limitations, such as high sugar and acid content products adhering on the wall and aggregation of ultra-fine powder. To meet the demand of consumer for a high food quality food product, it is essential to develop the technologies which are energy-saving and high efficiency. This is important to promote the development of agriculture, food and the pharmaceutical industry.

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List of tables

Table 1 Method classification and application of solid and liquid particles.

Micron-and Nanotechnoloy	**method**	**Principle**	**Applied scope**
Solid particulate materials	Jet milling	impacting, colliding and friction among materials by the energy of high-speed air flow or steam	applied to heat-sensitive or low melting point materials
	Ball milling	by friction, press and centrifugal force among milling medium	applied to many kinds of materials
	Colloid milling	by shearing, mixing and emulsifying, homogenizing	applied to soft, semi soft granular material

Liquid materials	High pressure homogenization	shear, turbulence and cavitation by the energy of high pressure force.	applied to liquid material or solid particle with liquid as carrier
	Ultrasonic homogenization	intense shear and pressure gradients by high intensity ultrasonic waves	applied to dairy products
	Microfluidisation	cavitation, turbulence and shear	applied to dairy products and producing nanoemulsions

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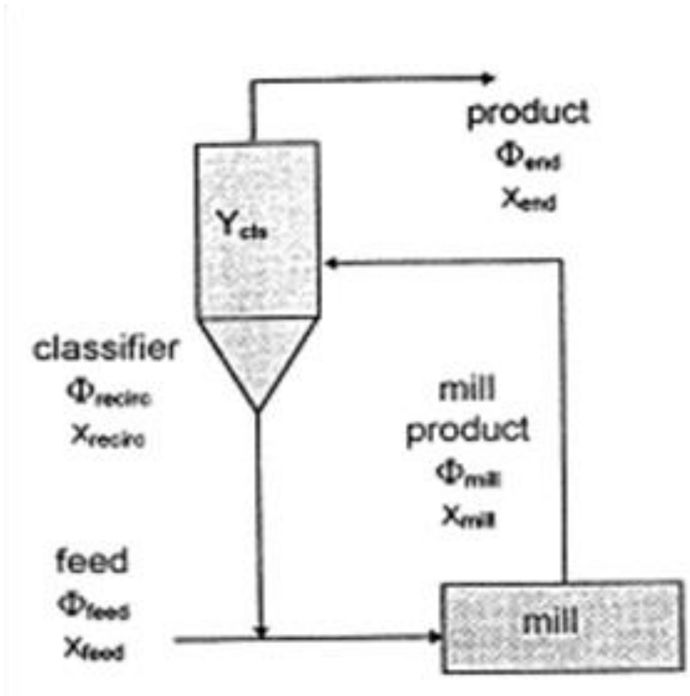


Fig.1. Model of a jet mill (Gommeren et al, 2000)

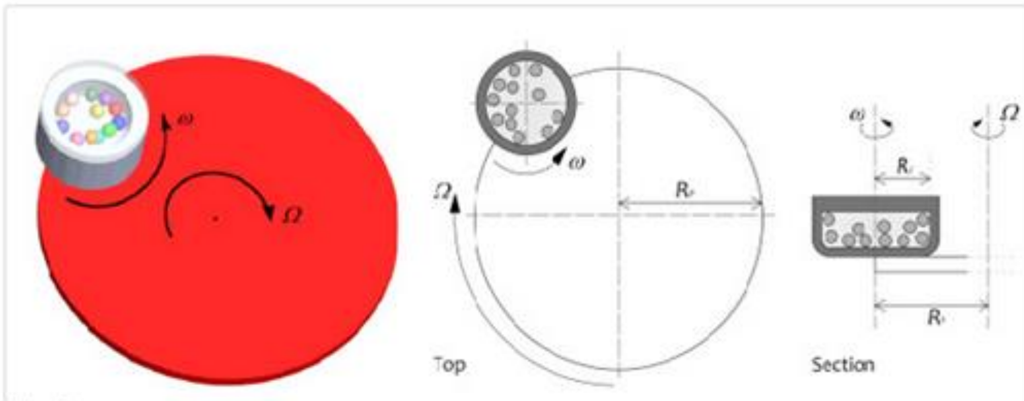


Fig.2. Schematic representation of planetary ball-mill. Left, three-dimensional view; middle and right, definition of the jar radius *Rj and* the distance axis of rotation and revolution *Rp* (Broseghini, M.et al, 2015)

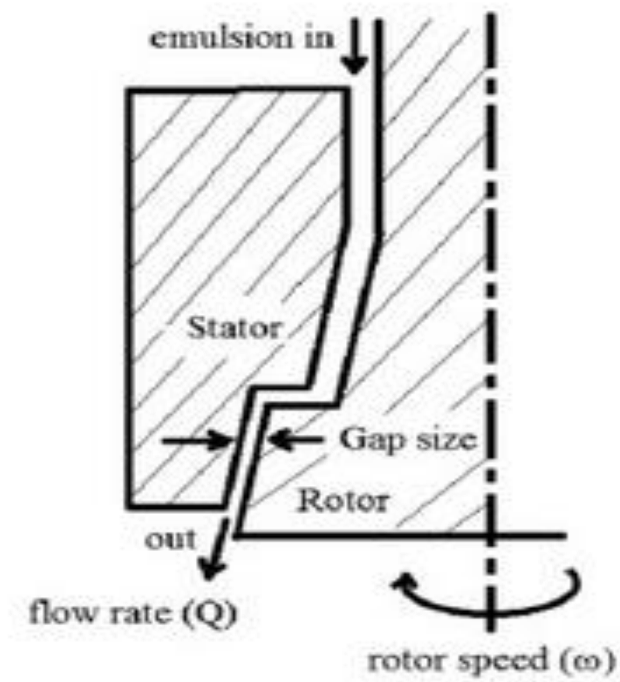
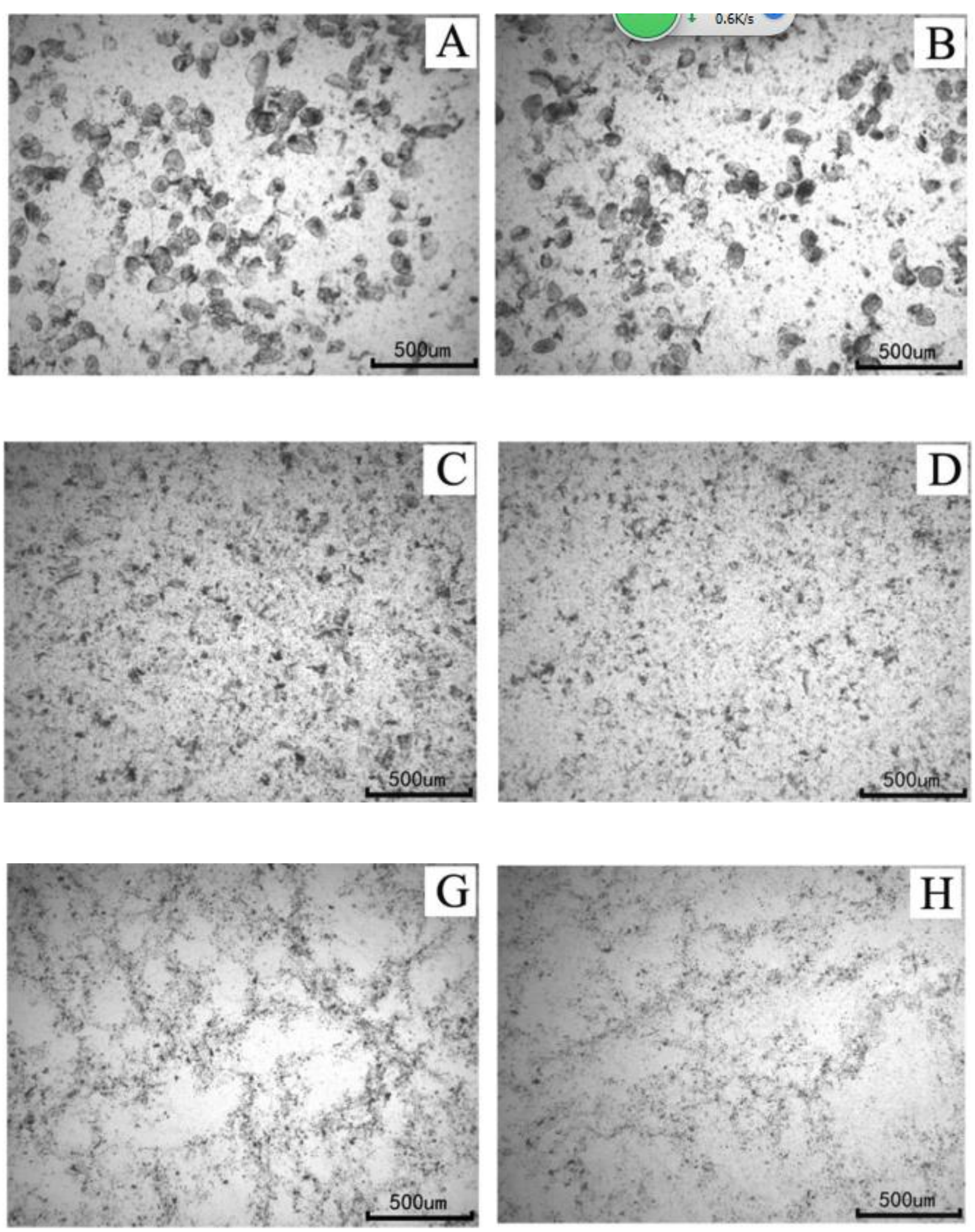


Fig.3. Schematic representation of a colloid mill (Maindarkar et al, 2014)


A
B
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C
D
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H
500um
500um
500um
500um
500um
500um

Fig.4. Effect of HPH on the microstructure of taro pulp: (A) non-homogenized sample (NH); (B) Homogenized at 0MPa; (C) 10MPa; (D) 20MPa; (E) 30MPa; (F) 40MPa; (G) 50MPa; (H) 60MPa. (Yu et al., 2016)