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Key Issues and Challenges in Spice Grinding

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Abstract

The process of grinding spices is an essential step in the food industry since it has a direct impact on the quality, flavor, and functional qualities of spice powders. Because of the increasing demand on a global scale, ensuring that grinding is both efficient and of good quality has become a priority. In this paper, a detailed overview of traditional and modern methods for grinding spices is provided. The analysis highlights the advantages and drawbacks of each approach, as well as essential operating parameters such as temperature, moisture content, and particle size used in the grinding process. Key issues, such as the formation of heat, the loss of nutrients, the risk of contamination, and the high consumption of energy, are investigated, along with the impact that these challenges have on the efficiency of grinding and the quality of the result. Technology advancements, such as cryogenic grinding, superfine grinding, and automation through the use of artificial intelligence and the internet of things, have been essential in solving some of these challenges while also introducing techniques that are sustainable and favorable to the environment. In the final section of the review, we will analyze the ongoing difficulties, the possibilities for the future, and the possibility of developing novel solutions to make the process of grinding spices more effective, environmentally friendly, and quality-oriented.

Keywords

Advanced Grinding Technologies, Challenges, Cryogenic Grinding, Spice Grinding, Superfine Grinding.

INTRODUCTION

Because of their taste, nutritional, and therapeutic characteristics, spices are essential components that are utilized all over the world worldwide. Historically dating back to ancient times, the spice trade has experienced substantial growth in response to the growing demand for products that are already processed and ready to be used. According to Grand View Research [1], the worldwide spice industry is estimated to be worth USD 14 billion as of the year 2022, and projections indicate that it would continue to expand at a robust rate of 5.5% yearly until the year 2030. Grinding processes that are efficient are essential for spice processors because of the growing trend toward healthier food products that are lightly processed. This tendency further stresses the necessity to preserve the nutritional value and scent of spices.

Bioactive compounds, essential oils, antioxidants, and other phytochemicals are the components that make up spices. These compounds are responsible for imparting flavor, scent, and potential health benefits. The grinding process, on the other hand, has the potential to severely impact these components, particularly through the formation of heat, the oxidation of volatile oils, and the loss of volatile oils [2]. Consequently, the optimization of grinding techniques is fundamental in order to guarantee the production of high-quality spice products that maintain their bioactivity. In addition, as a result of the rapid technological improvements in spice processing technology, businesses are working hard to strike a balance between cost-effectiveness, energy consumption, and product quality [3].

India is the country that produces the most spices, consumes the most spices, and exports the most spices. It also accounts for fifty percent of the global commerce. The aroma, flavor, and therapeutic benefit of Indian spices are well-known because of their sophisticated nature. According to Singh & Solanki [4], around 80–85 percent of the total seasonings that are produced in the country are eaten within the country itself. It is possible to evaluate the quality of any spice by analyzing both its inherent and extrinsic characteristics. A particular volatile oil or a chemical that is present in a spice is primarily responsible for the distinctive quality that distinguishes it from other spices. These chemicals are encapsulated inside the matrix of the plant cell and can be straightforwardly rendered accessible through grinding [5]. Powdered forms of main spice crops including red chili, coriander, turmeric, and others are preferred for consumption because of this reason. There is a significant potential for both export and domestic market for the ground powder. The grinding process is therefore an essential unit operation in the spice manufacturing industry. Grinding is a time-honored method that has been used for reducing the size of particles in order to produce powders that may be utilized as either intermediate or final products. According to Sahay & Singh [6], the purpose of grinding is to reduce the size of the particle through the use of numerous mechanical processes, including impact, compression, shear, and cutting. The most frequent types of grinding machinery for spices are the bowl mill, the pin mill, the roller mill, the hammer mill, and the plate mill [7].

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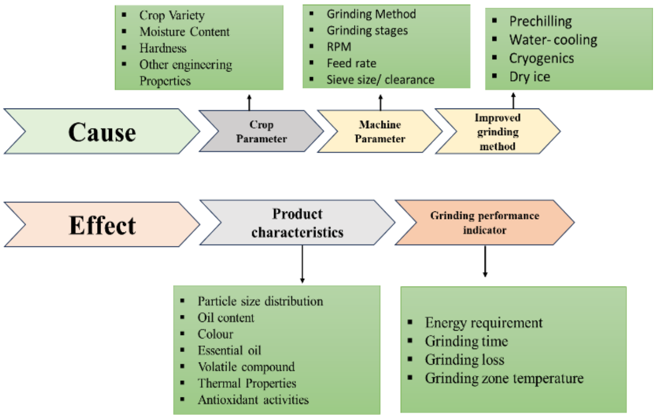

Figure 1. Cause and effect attributes of spices grinding process

OVERVIEW OF SPICE GRINDING PROCESSES

The process of grinding spices is an essential stage in the processing of spices since it has an effect on the flavor, texture, and bioactive content of the entire product. The procedure can be broken down into a few different approaches, each of which is suitable for a certain kind of spice and the consequences that are intended.

Grinding of Spices

Between the many stages of production in the food business, powders can be considered either intermediate products or end products [8]. Powders can be used in a variety of applications. The process known as grinding is comprised of a variety of processes that are carried out with the assistance of various pieces of machinery, including crushers, mincers, mills, cutters, shredders, grinders, homogenizers, and disintegrators [9]. Grinding requires the material to sustain ripping or breaking by a variety of mechanisms, including impact, compression, attrition, or cutting and shearing [10]. Once a significant number of tiny particles have been obtained from food items in their solid state through the utilization of size-reduction processes, powders are then created through the process of grinding. During the grinding process, a large number of mechanical forces are exerted on the material, which ultimately results in the development of particles that are more finely granulated. It is expected that the particles in the final products will have a smaller size if the amount of force that is applied is increased.

TRADITIONAL GRINDING METHODS

Traditional methods of grinding, including as stone mills and mortar and pestle, are still extensively utilized in small-scale operations. This is especially true in countries where artisanal or organic spice production is prevalent. However, despite the fact that they preserve a significant portion of the natural aroma and flavor, these techniques are labor-intensive, sluggish, and susceptible to contamination. They are also less effective in terms of maintaining a consistent particle size [11]. Mechanical grinders have become increasingly popular as a result of the necessity for increased efficiency in the grinding of some high-value spices, such as saffron and cardamom. Traditional methods are still preferred for handling these spices.

There is a significant contribution that spices make to the enhancement of the flavor and taste of processed meals. Because of the stimulating and digesting qualities that these spices possess, they are also utilized in the production of medicines. The grinding process, which is an age-old procedure similar to the grinding of other food ingredients, also contributes to the enhancement of these qualities. In the process of grinding spices, the primary objective is to get a smaller particle size while maintaining a high level of product quality in terms of flavoring and color. Energy is utilized to shatter a particle into a smaller size during the typical grinding process, which results in the generation of heat. The heat that is generated is typically harmful to the product, and it causes a certain amount of flavoring and quality to be significantly diminished. The fat that is found in spices typically causes additional issues and is a crucial factor to take into consideration when grinding. The temperature of the product rises to a level that is in the range of 42±95 °C during the grinding process. This temperature rise varies depending on the oil and moisture content of the spices; nonetheless, due to this temperature rise, spices lose a major portion of their volatile oil or elements that contribute to their flavor.

Size Reduction

During the grinding process, the materials are broken up into smaller pieces in order to minimize their size. However, during the process, the material is stressed by the action of mechanical moving elements in the grinding machine, and initially, the stress is absorbed internally by the material as strain energy. The mechanism of fracture is not completely understood, although it is generally accepted that the material is stressed. A fracture occurs along lines of weakness and the energy that has been stored is released when the local strain energy is greater than a critical level, which is a function of the material. It is true that some of the energy is absorbed in the process of creating new surface, but the vast majority of it is lost as heat. Within the context of the fracturing process, time is also a factor, and it would appear that the material will fracture at lower stress concentrations if these concentrations can be maintained for longer periods of time. Therefore, grinding is accomplished through the application of mechanical stress, which is then followed by rupture. The amount of energy that is required is contingent not only on the hardness of the material, but also on the material's inclination to crack, which is referred to as its friability.

Grinders

A grinder is typically used to further reduce the size of the product that is produced by a crusher. The grinding operation is essentially comprised of a grinding mill and a Pulverizer. Hammer mills, impactors, rolling compression machines, attrition mills, ball mills, and tumbling mills are some of the types of grinders that are used often in commercial settings. To convert crushed feed to powder, grinders are utilized. It is possible that the product obtained from an intermediate grinder would be able to pass through a screen with a mesh size of 40. On the other hand, the majority of the product obtained from a fine grinder would be able to pass through a screen with a mesh size of 200 and an opening of 74 micrometers. Feed particles that are no larger than 6 millimeters are accepted by an ultra-fine grinder, and the resulting size is typically between 1 and 50 micrometers. In terms of size and shape, cutters produce particles that range from 2 to 10 millimeters in length. Each of these machines does its tasks in a manner that is completely unique. Compression is the action that is most commonly associated with crushers. Impact and attrition are the two processes that are utilized in grinders; compression is occasionally mixed with attrition. Ultrafine grinders rely mostly on attrition to function.

Limitations in Conventional Grinding of Spices

A substantial amount of heat was produced as a result of the utilization of energy during the process of grinding any particle into a smaller size [12]. This heat generated resulted in a loss of product quality and quantity; however, the extent of this damage varies depending on the kind of oil and the moisture level of the seeds during the grinding process; however, the final product lost a significant amount of volatile oil, up to thirty to forty percent, as well as its original color. The percentage of volatile oil that is lost during standard grinding for various spices is as follows: thirty-seven percent for nutmeg, fourteen percent for mace, seventeen percent for cinnamon, seventeen percent for oregano, and thirty-two percent for caraway seed [13]. Produce of this kind does not meet the quality criteria that are recognized internationally; hence, it is not accepted by the countries that import it. In addition to volatile oil, the majority of spices contain a large quantity of fatty oils. These oils melt when exposed to heat, which makes it difficult for the grinder to operate continuously. This is because the melted fat causes the ground powder to stick to the surface of the grinder. The melting of fat as a result of heat is another issue that presents a challenge to the continuous operation of the grinder. This is because the melted fat causes the ground powder to adhere to the surface of the grinder. However, slow rotating roller mills have the potential to limit the loss of volatile substances; however, this has the potential to impact the energy efficiency of the grinder and is not suited for materials that are heat sensitive or contain a high percentage of fat [14].

MODERN GRINDING TECHNOLOGIES

Significant advancements in both productivity and quality have been made possible by the use of recently developed milling and grinding technology. In the spice industry, the following types of grinding machines are utilized the most frequently:

Hammer Mills

They are characterized by the presence of a rotating drum that is equipped with hammers that are responsible for breaking down the spice into smaller particles. Hammer mills are suitable for coarse grinding, but they have a tendency to generate a significant amount of heat, which can result in the loss of volatile oils, particularly in spices such as black pepper and turmeric [15].

Pin Mills

When compared to hammer mills, pin mills are utilized for finer grinding and produce more consistent particle sizes. Pin mills are also employed for grinding purposes. In the production of spices such as chili and coriander, pin mills are frequently utilized [2].

Jet Mills

Jet mills are perfect for creating ultra-fine powders with low heat generation since they use compressed air or gas as their source of energy. Because cinnamon and ginger are sensitive to the effects of heat, this method is frequently utilized for the production of high-value spices such as cinnamon and ginger [16].

Micro-Pulverizer

A micro-pulverizer is a high-speed hammer and screen mill that reduces the size of the material being processed by performing mechanical impact on the material. When it comes to size reduction, this technique is distinguished by its relatively high energy and short residence time, which helps to reduce the amount of heat that is generated during the milling process. The feed material that is going to be crushed is brought into the mill by means of a gravity feed hopper that is equipped with a slide that can be adjusted to manage the feed material. The material is crushed by the hammers or blades and the serreted liners that are placed between them. A powerful blower is used to continually suction the ground materials through a screen classifier. The materials are then transported down the pipe and into a cyclone drum for the purpose of bagging. In order to obtain a product, the blower ensures that there is a continuous flow of air within the grinding chamber, and it also cleans the screen on a continuous basis. By utilizing sieves that have the necessary aperture, it is possible to alter the particle size of the material that has been ground over a wide range.

Mini Pulverizer

The Mini Pulverizer is made up of a heavy-duty body made of stainless steel and mild steel. It has a feeding hopper that is equipped with a feed regulator slide. The body of the pulverizer is inlaid with a delivery trough attached at the bottom, and another delivery trough is attached at the end where the discharged material is collected. In a ball bearing housing, the rotor and beater are attached on a shaft, and they rotate at a speed ranging from 4500 to 6000 revolutions per minute. To support the entirety of the device, a sturdy steel channel stand has been fitted.

Cryogenic Grinding

The study of extremely low temperatures and their use on a variety of materials, including biological products, is referred to as cryogenics studies. Applications of cryogenics can be found in a wide variety of fields, including but not limited to: space research, electronics, automobiles, the manufacturing industry, sports and musical instruments, agriculture, biological science, and manufacturing. When it comes to food, namely spices and condiments, cryogenic freezing is an extremely useful technique. Although there is a wide variety of cryogens that can be used to achieve the requisite low temperature, liquid nitrogen (LN2) is the cryogen that is most commonly utilized in the process of food grinding. The utilization of low temperatures constitutes a prospective avenue for the production of an end product of superior quality, characterized by enhanced flavor and the retention of volatile oil.

Cryogenic grinding has emerged as a key breakthrough in the processing of spices, particularly for spices that are sensitive to heat, such as cardamom, ginger, and turmeric. This method entails giving the spices a chilling treatment with liquid nitrogen before grinding them [17]. This helps to prevent the loss of volatile oils and bioactive components [17].

KEY ISSUES AND CHALLENGES IN SPICE GRINDING

Heat Generation and Volatile Loss

Heat generation is the most major problem that arises during the grinding of spices. Heat has the potential to damage the essential oils, antioxidants, and active chemicals that are present in the spice. For example, tests have demonstrated that the high temperatures generated during grinding can cause the curcumin content of turmeric to fall by as much as thirty percent on average [18]. In addition, the volatile molecules that are responsible for the aroma of spices such as black pepper, cinnamon, and cardamom might be lost if they are exposed to extreme heat [15].

Particle Size Uniformity

Finding a way to achieve a consistent particle size is an essential necessity for preserving the quality of the product. When used in products such as spice mixes, spices that have variable particle sizes might result in different flavors being distributed throughout the product. The traditional grinding procedures, particularly when it comes to manual operations, have a difficult time producing particles of a consistent size. Differences in spice qualities like as moisture content, density, and fibrousness can lead to grinding that is inconsistent even in mills that are equipped with industrial-scale machinery [2].

Crop Parameters

The term "crop parameter" refers to a set of characteristics that encompasses engineering aspects such as variety, moisture content, and hardness. The conditions in which grains are grown have a considerable impact on the weight of a thousand kernels, the amount of ash that is present, as well as the physical and chemical qualities of grains [19]. One of the most important factors that determines the particle size distribution of ground product and the amount of grinding energy is the crop's moisture content. The brittleness and tempering conditions of the powder have an effect on the particle size, starch damage, milling yield, and functional qualities of the powder being processed [20]. Additionally, the grinding process is impacted by the kernel's weight, size, shape, and virtuousness in addition to its hardness. The shape and size of the grinding machine are two of the most important factors that determine the operational conditions and the machines themselves [21].

Parameters of the Machine

The rotor and grinding tool speed, feed rate, grinding time, as well as the temperature of the grinding zone and the amount of energy required, are all examples of machine parameters. The selection of the grinding mechanism is the first and most important step, taking into consideration the significant impact it has on the distribution of particle sizes. An assortment of grinding machines, including a hammer, ultrafine, plate, roller, pin, ball mill, and hand-pounding methods, are utilized for the purpose of grinding various spices [7]. The efficiency of the grinding process is impacted by certain aspects of the mill, including its design, operational, and functional parameters. The arrangement of the rollers, the speed, the type and number of rotors, the distance between the rollers and plates, the flutes profile, the diameter of the plate, the size of the opening or clearance between grinding components, and other factors are included in these parameters. It is the grinding process or principle that is used that determines the specific energy consumption and powder qualities that are determined. A hammer mill, for example, is more energy-efficient than a knife mill and generates particles that are finer with a higher degree of precision [22]. There is a relationship between the specific energy consumption and the distribution of particle size, and comminution rules illustrate this relationship. Through the utilization of intermediate screens, a variety of approaches were utilized in order to target aperture sizes that were rather tiny [23]. Rittinger's constant, kick's constant, bond's index, total surface area, average particle size, grinding efficacy, and yield were all connected with regard to these parameters, which were modified either alone or in combination [7]. These parameters were affected either individually or in combination.

Risks of Contamination and Safety

When it comes to grinding spices, cross-contamination is a big risk, particularly when processing several kinds of spices in the same piece of equipment. According to Raghavan [11], improper cleaning techniques might lead to allergen contamination, which can have an adverse effect on customers who are sensitive to particular spices. Furthermore, the utilization of grinding equipment of poor quality might result in the incorporation of metallic or other potentially hazardous components into the spice, so rendering it unfit for human consumption.

Energy Consumption

The grinding process is one that requires a significant amount of energy, and as the cost of energy continues to rise, the spice sector is under increasing pressure to optimize its energy use. Cryogenic grinding, for instance, can cut energy consumption by as much as forty percent when compared to conventional processes, making it a more environmentally friendly alternative [3]. The increased initial setup cost of cryogenic systems, on the other hand, may discourage smaller processors from adopting this technology.

ADVANCES IN SPICE GRINDING TECHNOLOGIES

Cryogenic Grinding

A major step forward in the processing of spices has been the introduction of cryogenic grinding, as was mentioned earlier. One of the most significant advantages of cryogenic grinding is that it helps to maintain the integrity of essential oils and bioactive substances. The procedure involves using liquid nitrogen to cool the spices [3].This decreases the temperature during the grinding process, which prevents the spices from warming up and losing their volatile ingredient components. In particular, this is advantageous for spices such as chile, turmeric, and ginger, which lose their strong characteristics when they are subjected to heat.

Cryogenic Grinding

With the assistance of cryogenic fluids such as nitrogen in its liquid state (LN2), the temperature increase that occurs during the typical grinding operation can be reduced to manageable levels. The material becomes brittle as a result of this low temperature. As the grinding process continues, this contributes to the finished product having particles that are finer in order to get the desired result. During grinding phenomenon, this also makes it possible to raise the pace of feeding while simultaneously reducing the amount of power that is consumed [24]. On the other hand, grinding at lower temperatures helps to prevent other unwanted changes, like as oxidation and discolouration, from occurring; this is because the temperature is lower. The process of spice cryogenic grinding, also known as cryo-grinding, is considered to be a rather advanced technology; hence, there are just a handful of units now operational in India. Both freezing and chilling are approaches that can be used in order to produce an end product that has a volatile oil content that has been preserved. In addition, a low temperature can be achieved by circulating refrigerant or cold water around the grinding apparatus, or by combining whole spices with solid carbon dioxide or dry ice and then grinding them. Both of these methods are viable options. According to Singh & Goswami, [24], however, such systems are not practicable for large-scale industrial operations because of the inefficiency of the rates at which heat is transferred. Therefore, this presents a challenge. The field of cryogenics is concerned with temperatures that are on the order of -1500 °C and studies the behavior of materials when they are subjected to circumstances of low temperature. The extremely low temperature is achieved through the utilization of cryogens, which include liquid helium, liquid nitrogen, argon, neon, krypton, methane, hydrogen, and natural gas in liquid form, amongst other substances. Since all cryogenic liquids are in a gaseous condition while they are at ambient temperatures and pressures, it is necessary to get these gases down to a temperature that is lower than the atmospheric temperature in order to liquefy them. At temperatures lower than -1500 °C, the cryogens boil. Cryogens are stored in vessels known as dewar flasks, which are equipped with sufficient insulation. These vessels are used to store their contents.

Design Parameters of Cryogenic Grinder

During their time at the Indian Institute of Technology in Kharagpur (WB), Singh &Goswami [25], made significant contributions to the investigation and development of a cryogenic grinder that was specifically designed to be used for spices. A grinding system that was intended exclusively for cumin and clove was developed by them. Cryogenic temperature during grinding was found to be able to retain more volatile and enhanced quality of ground powder, according to the findings of their study on the influence of grinding temperature and number of ribs on grinding characteristics and quality of ground powders in terms of essential oil content. When Singh &Goswami [24] conducted a study on the impact of different grinding parameters on the quality of clove products, they discovered that sieve blockage occurred at temperatures exceeding -50 °C. During the process of constructing a cryogenic grinder for spices, they made the observation that feed rate, rotor speed, and sieve opening widths are some of the most essential design characteristics. Since that time, a number of researchers, notably, have produced many bench-top models of cryo-grinders [26]. One of these models is a pin mill that has a capacity of 120 kg per hour for grinding black pepper [14].

The Cryogenic Grinding process

Cryogenic grinding, also known as freezer grinding or cryo-milling, is a technique that involves reducing the size of solid materials in a cooling environment that is provided by cryogens. This is done in order to maintain the quality of the ground result. From the perspective of the food sector, this method is regarded as an efficient method of cooling or refrigerating a wide variety of items. The cryogen, which is in a liquid state and has a temperature of around -195.60 °C, provides the cooling effect that is necessary for pre-cooling the spices during this procedure. This is done in order to maintain the desired low temperature values by removing the heat that is generated during the grinding process. Not only does liquid nitrogen keep the temperature at a low level, but it also vaporizes into a gaseous state, which results in an atmosphere that is dry and inert. This provides an additional layer of protection for the spice's nutritional value. As a result of the pre-cooling of the raw spice and the continuous maintenance of a low temperature inside the grinding mill, the loss of moisture and volatile oils is reduced to a minimum. This allows the spice to retain its maximum flavor intensity per unit quantity during the grinding process, which ultimately results in a product of superior quality. In order to actualize the phenomenon of grinding and to design an efficient grinding system, the findings of the research on cryo-milling and the qualities of spices would be of particular use. Figure 2 illustrates the fundamental operation of a cryo-grinding system, which is a type of equipment that normally operates at low temperatures. In order to get the grinding process started, the compressor is started. The exit valve of the compressor is held slightly open in order to achieve the required pressure in the vessel containing liquid nitrogen (LN2), which is determined by the temperature that is to be maintained during the grinding process. During the process of the screw conveyor assembly, LN2 is prepared to be introduced into the distribution system. Both the grinder and the assembly of the screw conveyor are chilled to the needed grinding temperature, which is on the order of -160 to -700 °C. The speed of the conveyor can be set using a direct current motor with variable speed, and this can be done in accordance with the required feed rate to the grinder. Immediately after the sample material has been delivered to the inlet of the screw conveyor system, the grinder is activated and put into action. Immediately after the material has been processed through the pre-cooler, it is permitted to proceed to the grinder. In the range of -160 to -700 °C, the grinding take place at the temperature that has been established. When the temperature rises during the process of grinding or preparing powder, it is preferable to increase the rate at which liquid cryogen is flowing through the system. After the powder has been gathered in a bag that is coupled to the system at the output of the grinder, the nitrogen vapours are permitted to escape [27].

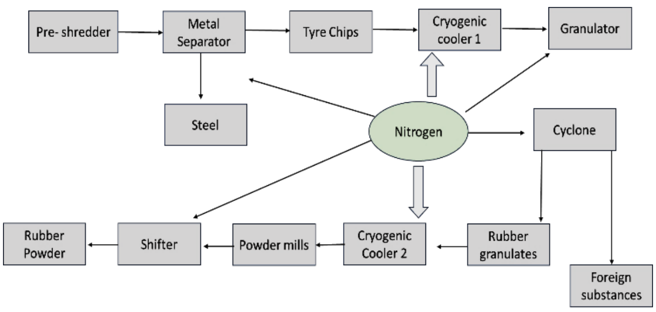

Figure 2. Typical Cryogenic grinding process flowchart

Advantages of Cryogenic Grinding System

The natural quality attributes of spices are preserved, ensuring their freshness and flavor are maintained throughout the process. Additionally, the system minimizes thermal fatigue and reduces the risk of fire, contributing to a safer and more efficient operation. It offers enhanced production capacity while providing excellent control over particle size, achieving a fineness of approximately 50 microns. Furthermore, the equipment experiences less wear and tear, ensuring durability and reducing maintenance requirements.

Disadvantages of Cryogenic Grinding System

The drawbacks of grinding with cryogenic technology include challenges such as the potential formation of ice around the system piping in humid environments. This can hinder the delivery of liquid cryogen, leading to process interruptions. Additionally, the technology poses economic challenges that need to be addressed, as both maintenance and operational costs are notably high, making it a less cost-effective option in certain scenarios.

Superfine Grinding

The particle size of the flour is an important characteristic that determines the functional property of the flour, which is the release of the active components [28]. It is also utilized in the process of evaluating the quality of finished products. It is considered to be one of the most effective strategies to lessen the problem that is associated with a big particle size of bran and germ for a customer [29]. Grinding is an important operation that occurs during the creation of powder. The process of superfine grinding is considered to be one of the most efficient methods for the production of micro, submicron, or nano powders (100 μm–1 nm). These powders are utilized for the purpose of preparing foods that are both convenient and ready to use.

Superfine grinding technology

The term "superfine grinding" describes the process of reducing the particle size of the material to the microlevel by the utilization of mechanical equipment [30]. The nature of the raw materials and the features of the product that are wanted both play a role in the different grinding technologies that are utilized in the process of superfine grinding. According to the materials, various technologies for superfine grinding have been developed. These technologies include cryogenic grinding, vacuum grinding, roller grinding, shear crushing, and airflow comminution. Additionally, equipment such as jet milling, universal pulverizer, vibrating mill, and ball mill are widely used in superfine grinding. These are among the devices that have been reported for grinding to a superfine level. Several procedures for superfine grinding have been demonstrated to exhibit a broad range of morphological qualities [31]. These properties include the appearance of particles that are fractured, ovoid, distorted, and irregular in shape. The most frequently reported superfine grinding device is the ball milling process [32].

Working principles of superfine grinding

The food sector has just begun to implement size reduction techniques that range from micron to nanoscale [30]. This technology is undergoing rapid development. A reduction in the size of the food powder particle is achieved through the process of superfine grinding, which results in an increase in the surface area. The grinding process results in the breakdown of cell walls, which in turn increases the bioactivity and extraction of nutrients into the product [33]. According to the findings of a study that was conducted using environmental scanning electron microscopy (SEM), the mechanical shear stress that occurs during superfine grinding has a substantial impact on the deterioration of Sanchi flower powders, which ultimately leads to an increase in surface area [34]. It is possible for the mechanical force that is utilized in the process of superfine grinding to bring about changes in the chemical composition of the material. These changes may include an increase in the ratio of surface area to volume, the rupturing of the material's cell wall, which results in an increase in accessibility, the release of biologically active compounds, and changes in the components of the diet. The application of mechanical force during the process of superfine grinding of chitin results in the destruction of intermolecular bonds between chitin molecules, which ultimately results in the release of bioactive chemicals. As an additional point of interest, the reactive surface is expanded to a greater extent by the smaller particle size [35]. One of the factors that contributes to an improvement in the quality of the superfine ground powder is a smaller particle size [36]. This increases the mass transfer and makes it possible to create extracts that include a greater number of bioactive compounds. Based on the research, it appears that the mechanical pressure that is applied during the grinding process is mostly responsible for the breaking of the cell walls of the food ingredients. An increase in surface area and a reduction in particle size are the two factors that give rise to the release of active molecules as well as an enhancement in the nutritional and sensory quality of the substance.

Advantage of superfine grinding over conventional grinding

Functional food and nutraceuticals are made via breakthrough superfine grinding [37]. Conventional grinding cannot achieve these contributions due to the product's high fineness. Superfine grinding releases cellular sustenance that the body can swiftly absorb, preserving high-quality, nutrient-rich, and physiologically active components [38]. Many benefits arise from superfine grinding. Reducing dietary component particle sizes to micro- or nanoscale will modify their structure and surface area and introduce new properties. Novel academic and business applications are suggested for surface, minisize, macro quantum channel, optical, magnetic, mechanical, chemical, and catalytic capabilities [39]. Due to its time, solvent, and energy savings, superfine grinding technique is drawing interest in functional component extraction. Superfine grinding improves extraction efficiency and green powder processing [40]. Mechanical grinding required more energy than superfine grinding. Better than standard grinding powder, superfine ground powder reduces interfacial tension and steric hindrance. Superfine crushed powder changed physicochemical properties, according to [41]. This includes increased hydration and fluidity, bioavailability and bioactivity in vivo or in vitro, radical scavenging, and lowest interfacial tension. Superfine grinding improves whole wheat's cooking, cohesiveness, toughness, and microstructure [29].

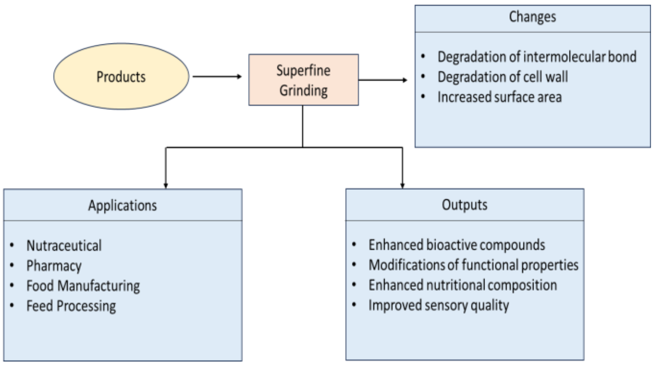

Figure 3. Working Principles of Quality improvement by superfine grinding

Applications of superfine grinding technology

The superfine grinding process has demonstrated the potential to be utilized in a wide variety of subject areas [42]. Superfine grinding is utilized in a broad variety of industries, including the production of paper, ceramics, pharmaceutics, electronic materials, and chemicals, with the purpose of reducing the size of particles and improving the surface of reactive substances. The utilization of superfine grinding is utilized in the process of developing new functional materials for a wide range of industries, including biotechnology and food items manufacture [43]. Research conducted has demonstrated that the utilization of superfine grinding technology has the potential to be utilized in the manufacturing of nutraceuticals, medicines, health foods, component extraction, and animal feeding [44]. Powders of *L. edodes* that have been ground extraordinarily finely have the potential to be utilized in a wide range of sectors as additives for food or pharmaceutical products [45]. The smaller particle size of the superfine ground *D. Officinale* products can make it easier to incorporate into food [46]. As a result, the powder that is produced from the superfine ground could be utilized in the production of nutraceuticals and pharmaceuticals. As a result of the fact that this particular method of size reduction has demonstrated the possibility of application in the biomedical and food production industries, the technology of superfine grinding has garnered a great deal of interest [47].

Automation and AI Integration

When it comes to grinding machines, automation that is driven by artificial intelligence helps achieve consistent particle size, boost yield, and minimize labor expenses. In order to guarantee the best possible performance, sophisticated algorithms are able to keep track of important characteristics such as the speed of grinding, the pressure, and the temperature. These technologies not only improve efficiency but also reduce the dangers of contamination by guaranteeing that proper cleaning cycles are followed and superior quality control is achieved [2].

CHALLENGES AND FUTURE PROSPECTS IN SPICE GRINDING

Persistent Challenges in Spice Grinding

The industry of spice grinding is confronted with a number of ongoing issues that have an effect on the efficiency, product quality, and sustainability of the industry. Among the most significant difficulties are:

Energy Costs

Grinding procedures are extremely energy-intensive, and spice processors are feeling the strain as a result of increased global energy prices when compared to other industries. Additionally, the grinding stage is often responsible for a sizeable amount of the overall energy consumption that occurs throughout the manufacturing of spices. For example, research conducted reveals that the amount of energy that is consumed during the grinding process can account for as much as 25% of the total energy that is needed in the production of food [3]. Consequently, this leads to a rise in manufacturing costs, particularly for grinding methods that require a significant amount of energy, such as hammer mills and jet mills.

Risks of Contamination

Contamination during the grinding of spices continues to be a serious problem, particularly when different kinds of spices are handled using the same equipment. Cross-contamination can occur when there are residual spice particles or when there is insufficient washing between batches. This can result in allergies or adulterants being introduced into the produced goods. Additionally, the use of grinding equipment of poor quality can result in the introduction of impurities such as metal shavings into the final product, which raises issues regarding the safety of food [11]. When it comes to large-scale operations, where it can be difficult to maintain rigorous sanitary standards, these hazards are especially significant.

Nutrient Loss and Degradation

The development of heat during the grinding process is another significant obstacle, as it results in the loss of volatile oils, antioxidants, and key nutrients. This is a significant problem since it contributes to the degradation of the nutrients. Because of the high concentration of essential oils that they contain, spices such as cardamom, black pepper, and turmeric are particularly susceptible to the development of nutritional degradation. The curcumin concentration of turmeric can be reduced by as much as thirty percent or more when it is treated to extreme heat during the grinding process, according to research carried out by [18]. There is a reduction in the nutritional content of the spice as a result of this, as it not only impacts the flavor but also the health advantages of the spice.

FUTURE SOLUTIONS FOR SPICE GRINDING

Innovation, sustainability, and efficiency improvements will be the focus of future solutions in spice grinding in order to meet the continuous issues that have been encountered. Among the most important solutions are:

Sustainable Technologies

The industry is shifting toward grinding technologies that are more energy-efficient as a response to the rising cost of energy. A number of technologies, like cryogenic grinding, have garnered attention due to their capacity to lessen the amount of energy that is consumed while simultaneously retaining the flavor and bioactive ingredients of spices. Cryogenic grinding, which involves cooling the spice material using liquid nitrogen before grinding, helps avoid the formation of heat that damages essential oils and antioxidants [3]. Cryogenic grinding includes coolness of the spice material. Through the provision of energy savings as well as an improvement in product quality, such technologies are anticipated to be the driving force behind the future of spice grinding.

Automation

It is more than likely that automation will become an essential component of spice grinding processes in the future. Through the regulation of temperature, pressure, and particle size distribution, artificial intelligence-based systems and automated monitoring technologies can assist in the optimization of grinding processes. This helps to ensure consistent product quality while simultaneously decreasing the amount of human interaction. Automated systems are also advantageous in terms of increasing production while maintaining rigorous quality requirements, which helps to address the problem of a lack of available labor in the spice processing business [2]. Additionally, the use of automatic cleaning routines within grinding equipment will assist in the reduction of contamination concerns, along with the maintenance of hygiene and the prevention of cross-contamination between various batches of spices.

Eco-friendly Methods

Sustainability will be the driving force behind the future of spice grinding, particularly as the food industry places a greater emphasis on lowering its carbon impact. Grinding facilities could benefit from the implementation of renewable energy sources, such as solar and wind power, as one example of such a solution. Composting and the use of spice dust as animal feed are two examples of waste reduction initiatives that are anticipated to gain popularity in the near future. Researchers are also investigating alternate grinding technologies that are friendly to the environment and reduce the amount of damage done to the environment while maintaining a high level of product quality [48].

TRENDS IN SPICE GRINDING

The development of more advanced grinding technologies and the enhancement of quality control measure Continuous technological breakthroughs and the ever-evolving expectations of consumers for items of higher quality will be the driving forces behind the developments that will shape the future of spice grinding. A few noteworthy patterns are as follows:

Advanced Grinding Technologies

The development of technologies that are capable of accomplishing superfine grinding is one of the most significant trends. The production of powders with an extremely tiny particle size is the result of superfine grinding. This type of grinding is desired because it increases the bioavailability of active chemicals, particularly in spices such as ginger and turmeric. Another benefit of using fine powders is that they improve the flavor extraction process in spice mixtures and processed goods. Even though superfine grinding requires a greater amount of energy input, research is currently being conducted to find ways to improve the energy efficiency of these operations. Products that have superior flavor profiles and better bioactive qualities will be produced as a result of the trend toward more micronized spices and improved particle size management [48].

Improved Quality Assurance

The increasing demand from customers for items that are organic, of high quality, and free of preservatives has resulted in the introduction of more stringent quality assurance processes in the spice grinding industry. Real-time quality monitoring, which makes use of sophisticated sensors and analytical methods like gas chromatography (GC) and high-performance liquid chromatography (HPLC), is gaining popularity as a means of ensuring that ground spices retain their flavor, fragrance, and nutrients in a consistent manner. In the future, it will be vital to have technologies that monitor the essential oil content, particle size, and moisture levels during the grinding process in order to ensure that product quality is maintained [18].

Hybrid Grinding Systems

Another innovation that is now gaining traction is the incorporation of many grinding techniques into a single system. This is known as hybrid grinding systems. The goal of hybrid grinding systems is to reach the highest possible levels of both efficiency and product quality by combining the benefits of a number of different technologies, such as cryogenic and superfine grinding. As an illustration, a hybrid system might initially employ cryogenic grinding in order to protect essential oils, and then proceed to utilize superfine grinding in order to reduce powder particle size. This combination has the potential to assist minimize the limits of various grinding processes and maximize performance for particular different types of spices [3].

CONCLUSION

The food industry relies on spice grinding to meet global demand for high-quality spice powders. This review illuminated spice grinding process evolution. Classic procedures and advanced technologies each have pros and cons. The effectiveness and quality of spice grinding are still affected by major issues. The issues are heat generation, particle size uniformity, nutritional loss, and contamination. Recent advances like cryogenic grinding, superfine grinding, and automation and smart technology integration may solve these challenges.

Despite advances, long-standing issues demand further research and innovation. These issues include energy use, environmental impact, and bioactive component retention. The future of spice grinding depends on sustainable, energy-efficient, and eco-friendly technologies. These methods could bring spice powders to market cheaper and safer while decreasing their environmental impact. The spice grinding sector will be able to meet current demands and adapt to global trends and consumer preferences. This will keep the sector growing and helping the food industry.

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