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Advancements in Coffee Manufacturing: From Dehydration Techniques to Quality Control

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Abstract
This comprehensive study delves into advanced dehydration techniques and processing technologies in the realm of coffee manufacturing. It offers a comparative analysis of these techniques, specifically focusing on green coffee beans and instant coffee production. The examination encompasses the pivotal steps of grading, roasting, grinding, extraction, and dehydration, which form the core of the coffee manufacturing process. In the context of instant coffee production, two primary dehydration methods, spray-drying and freeze-drying, are scrutinized for their roles in water removal from coffee extracts and slurries and their impact on final product quality and efficiency. This study emphasizes the significance of dehydration processes as the linchpin of manufacturing optimization, considering their prominence in coffee production plants. Furthermore, the research extends to investigate the diverse extraction techniques, additional processes, and critical technologies, such as agglomeration, used in the production of coffee instant powder. Quality control, life cycle analysis, and assurance are scrutinized to provide insights into the overall sustainability of coffee manufacturing. The examination also explores the environmental impact, byproducts, and nuanced properties of coffee powder across different production systems. In essence, this review serves as a valuable resource for industry professionals, researchers, and coffee enthusiasts, offering a holistic understanding of advanced coffee dehydration techniques and their impact on quality, efficiency, and sustainability in the context of both green coffee beans and instant coffee production.

Keywords Coffee manufacturing · Dehydration techniques · Green coffee beans processing · Spray-drying · Freeze-drying · Instant coffee production

Introduction

Coffee, widely acknowledged as the "world's favorite beverage", plays a significant role in the everyday routines of millions of people worldwide [1]. The rich aroma and diverse flavors of coffee have made it a cultural icon, transcending borders and bridging diverse societies. Apart from its highly appealing taste, coffee is essential to many facets of human life. From an economic standpoint, it powers a multibillion-dollar sector, supporting countless people who work in its production, distribution, and processing. Socially, it acts as a spark for meetings, conversations, and relationships, encouraging interpersonal exchanges and communication. Furthermore, its chemical complexity has spurred a myriad of scientific investigations, offering insights into both its nutritional value and potential health benefits.

The global coffee industry has been experiencing steady growth in production and consumption over the past few years, with exports playing a significant role in the market's expansion. The International Coffee Organization (ICO) reports that, in the 2022–2023 crop year, 168.2 million bags (60 kg each) of coffee were produced globally, a 0.1% rise from the year before. In the forthcoming coffee year of 2023/24, it is anticipated that the total production will rise by 5.8% to reach 178.0 million bags. This increase is attributed to Arabica coffee, with output expected to reach 102.2 million bags, and Robusta coffee,

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which is projected to increase to 75.8 million bags [2]. Concerns about sustainability, the advent of e-commerce, and the growing demand for specialty coffee are the main drivers of this expansion. Figure 1 below states the recent production as observed from the ICO.

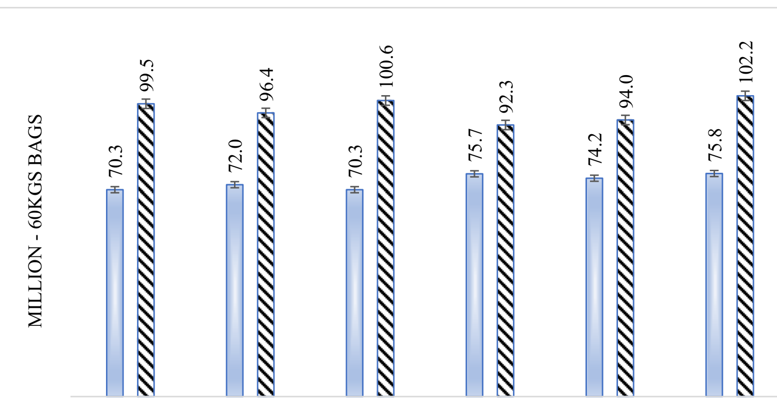
Cultivating a coffee tree is a challenging task. It typically takes approximately two years for a coffee seed to develop into a small, mature tree ready for production. Extensive preparation over many years is necessary to establish a dependable coffee farm that can sustainably produce coffee. Globally, an estimated 120 million people depend solely on the coffee market as a source of income. Climate change, pests, disease, and coffee leaf rust impacted 50 to 85% of Central America's production in 2012 [3]. This is overwhelming evidence that coffee production has been affected by climate change. Severe weather (e.g., high temperatures and heavy rain) could greatly influence the farming of coffee trees. As a result, the harvesting season is not going to be in favor of the farmer as well as the drying of the coffee beans where sometimes needs sunny and dry weather.

The journey of coffee, from its cultivation on the coffee farms to its final preparation as a brewed beverage, is a complex and intricate process. Central to this process is the removal of moisture from coffee beans, a critical step that directly impacts the quality, efficiency, and sustainability of the coffee manufacturing industry [4]. The dehydration process in coffee manufacturing is pivotal as it ensures the preservation of the beans and enhances their shelf life. Historically, the drying process in the sun and natural air have been employed to lower the moisture content of coffee beans. But because of how reliant these techniques are on the weather; the final output may differ and the processing time may increase. Additionally, such traditional practices have a limited capacity to retain the coffee's aromatic and flavor compounds.

The field of sophisticated dehydration methods and processing technology in the coffee industry has attracted widespread interest from academics, industry leaders, and coffee enthusiasts. Recent advancements in dehydration methods, including vacuum, spray, and freeze-drying, have significantly improved the quality, efficiency, and sustainability of coffee production [5]. These techniques offer precise control over the dehydration process, ensuring consistent quality that is often challenging to achieve in the food industry. Moreover, they lead to a substantial reduction in processing time and resource consumption, offering potential enhancements in sustainability. Implementation of these sophisticated dehydration procedures and processing technologies has the potential to revolutionize the coffee manufacturing business, increasing productivity, promoting sustainability, and enhancing product quality [6]. Through scientific investigations and comparative analyses, a deeper understanding of the benefits and challenges associated with these technologies can be gained, guiding the coffee sector towards a more flavorful and sustainable future. Coffee producers are encouraged to adopt cutting-edge dehydration methods and processing technology to streamline operations, ensure consistent quality, reduce waste, and meet consumer demands. Furthermore, advancements in these areas can contribute to improved sustainability standards within the coffee industry by reducing energy, water usage, and environmental impact, including greenhouse gas emissions [7].

In this comprehensive analysis, the cutting-edge dehydration methods as they relate to the production of both instant coffee and green coffee beans are delved into. The escalating demand for premium coffee underscores the need to comprehend the technological advancements influencing its manufacture. This research contributes significantly to the ongoing expansion and development of the coffee industry, benefiting customers and stakeholders alike. This review aims to investigate the various dehydration methods

Fig. 1 The production of coffee worldwide [2]



	2018/19	2019/20	2020/21	2021/22	2022/23	2023/24
Robusta	99.5	96.4	100.6	92.3	94.0	102.2
Arabica	70.3	72.0	70.3	75.7	74.2	75.8

employed in coffee production and their effects on the flavor, aroma, color, and solubility of coffee. Processing techniques, nutritional content, sensory attributes, and consumer preferences between green coffee beans and instant coffee will be scrutinized and compared. This comparative analysis will offer consumers insightful information to make informed decisions regarding the benefits and drawbacks of each type of coffee. Moreover, the exploration extends beyond coffee as a beverage, examining the technical, economic, and cultural aspects that underscore coffee's significance in society. This review is intended to be an invaluable resource for researchers, industry professionals, policymakers, and coffee enthusiasts, offering a holistic examination of advanced dehydration techniques and processing technologies, their implications for quality, efficiency, and sustainability, as well as their future directions.

Overview of Coffee Processing Stages

Coffee processing is a multifaceted series of critical stages that metamorphose harvested coffee cherries into the beans that consumers buy and brew. The primary processing methods encompass dry or natural processing, wet processing, and semi-washed processing, each of which involves diverse phases significantly shaping the flavor and quality of the final coffee product [8]. It all begins with selective harvesting, where ripe coffee cherries are meticulously handpicked, leaving unripe ones to mature on the tree. Two main harvesting techniques, strip picking, and selective picking, are employed. Subsequently, in the wet processing method, depulping commences, with the outer skin and pulp of the cherries removed by a pulper machine, revealing the coffee beans. After depulping, the beans undergo fermentation in water tanks, which entails soaking them to eliminate the remaining pulp and mucilage. The duration of fermentation, typically 24 to 48 h, plays a pivotal role in flavor development. Following this, a thorough washing takes place to ensure the removal of any residual mucilage, contributing to the clean and bright flavor of washed coffees. The next stage, drying, offers multiple techniques, including patio drying, machine drying, and sun drying, where the beans are exposed to different drying methods. Milling then follows, involving hulling to remove the parchment layer covering the bean, leaving behind the green coffee bean, thus refining the coffee's quality. Subsequently, grading and sorting occur based on bean size and quality, facilitating the separation of specialty and commercial-grade beans. Roasting marks a pivotal transformation, as green coffee beans are subjected to heat to unlock their unique flavors and aroma. The roasted coffee is subsequently packaged for distribution and sale, with packaging methods significantly impacting freshness and shelf life. Finally, the journey culminates in brewing by consumers who utilize various methods such as pour-over, espresso, or French press, each playing a pivotal role in shaping the taste and aroma of the coffee cup. These intricate stages collectively contribute to the diverse world of coffee, where every step influences the quality, flavor, and ultimate sensory experience [9–13].

Generally, coffee beans are subjected to thermal, mechanical, and chemical processes after the harvesting season, which is somewhat roughly starting in April and ending in June each year. Processes differ depending on the growing region, farmer capability, and water or equipment availability in that region. Advanced processing needs advanced equipment that might not be available in any part of the world where coffee grows. However, the following diagram is an illustration flowchart of the post-harvesting processes that are needed for the coffee cherries. Figure 2 shows what is called dry or wet processing and each step of processing in green coffee.

The steps of processing green coffee beans are illustrated in Fig. 2. First, coffee cherries are washed with water to remove remaining residuals (i.e., dirt, stones, insects, twigs, and leaves). In this stage, the bad fruit will flow on the surface of the water and be removed. Second, processing is divided into two main sections which are wet and dry processing. In wet processing, the outer layer of skin is removed mechanically by pressing the fruit altogether [15, 16] This is adding to the capital cost of the process. Both special equipment and a very high amount of water are used. Later, the pulp and pectin layers, as shown in Fig. 3, are fermented to break down the cellulose cell in water. Mechanical force might be used to reduce the water used by scrubbing the parchment layer. Afterward, the green coffee beans are dried. In the dry processing, the whole cherries are dried first, and then layers are removed without even washing. There is also a hybrid method where the cherries are washed, which has been indicated as a dry process in Fig. 2. In this method, cherries are washed and then dried as a whole fruit. Dry and wet processes provide a significant difference in the final product taste, as stated by experts. It should be mentioned that the whole cherry has a much higher moisture content than the bean itself. This increases the risk of having microbial spoilage during the drying process.

The first significant water removal happens right in the green coffee beans' first processing, washing in this case. This is mainly in the farm, not on the industrial scale. Depending on the weather and the farmer's capability, this drying, which reduces the moisture content significantly from about 50 to 11%, occurs on the farm. There are two well-known approaches, natural drying and mechanical drying, or both are used sometimes. Those types of drying are dependent on the weather (rainy, sunny, or cloudy day) and moisture content of the air in that region. Also, another factor can be the space available to dry the coffee.

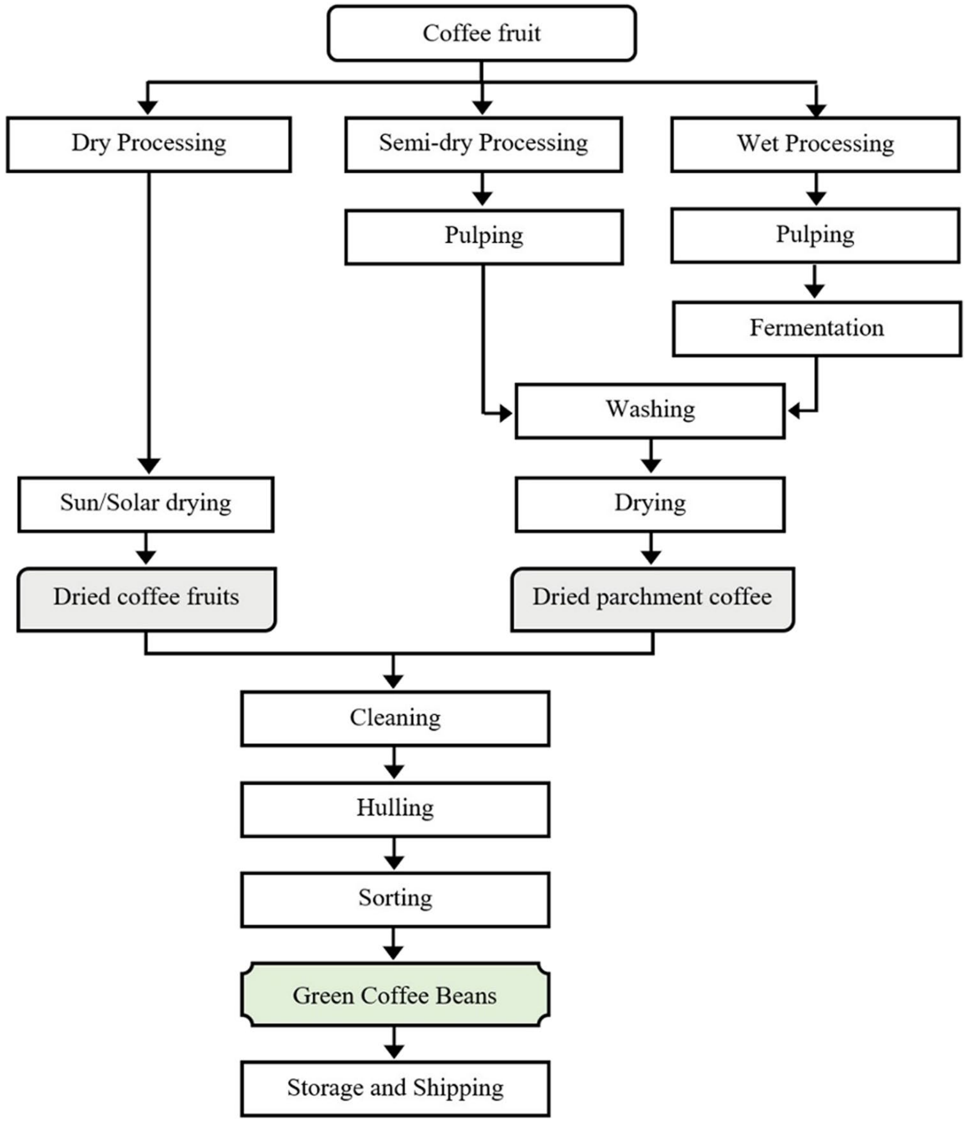


Fig. 2 Flowchart of the green coffee beans processing steps [14]

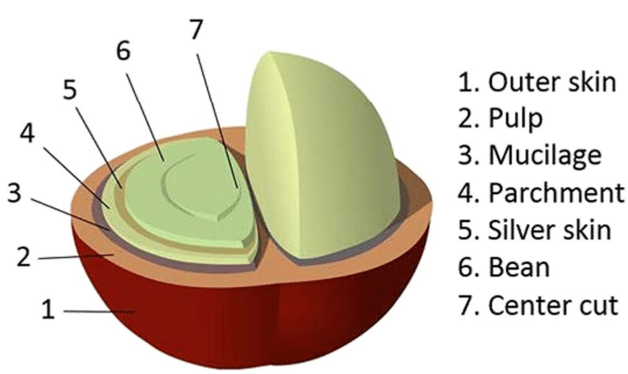


Fig. 3 Illustration of the coffee fruit structural layers [17]

Role of Dehydration in Coffee Production

Dehydration plays a crucial role in coffee production, affecting various aspects of the coffee bean's quality and flavor. This process involves removing moisture from the beans to achieve the desired characteristics and shelf stability. Dehydration significantly influences the flavor profile of coffee beans. During the drying process, various chemical reactions occur within the beans, leading to the formation of volatile compounds responsible for the characteristic aroma and taste of coffee. The rate and method of dehydration can significantly impact these reactions and subsequently affect the final flavor.

One of the critical reactions that occur during dehydration is the Maillard reaction [18, 19]. This reaction involves the interaction between amino acids and reducing sugars present in the coffee beans, resulting in the formation of melanoidins and other flavor compounds. The Maillard reaction is responsible for creating desirable flavors such as caramel, chocolate, and nutty notes in coffee [20]. Dehydration also plays a role in preventing or delaying the staling process in coffee beans. Staling refers to the gradual deterioration of flavor and aroma over time due to oxidation and other chemical changes. Proper dehydration helps preserve the freshness and quality of coffee by reducing moisture content, which inhibits enzymatic reactions that lead to staling [21]. The level of dehydration can influence the acidity and body of coffee. Acidity refers to the perceived brightness or sharpness in flavor, while body refers to the mouthfeel or viscosity. Dehydration affects these attributes by altering the concentration of organic acids and polysaccharides in coffee beans [21]. The balance between acidity and body is crucial in achieving a well-rounded and enjoyable cup of coffee.

Coffee beans need to reach an appropriate moisture content level during dehydration to ensure long-term stability without compromising flavor. The ideal moisture content for green coffee beans is typically around 10–12% [21]. This level stops over-drying, which can cause brittleness and flavor loss, and excessive moisture, which can cause mold growth and spoiling. When preparing coffee beans for storage and transit, dehydration is essential. By reducing moisture content, the risk of microbial growth and spoilage is minimized. Properly dehydrated beans can be stored for extended periods without compromising quality or flavor [21]. Moisture content is also an essential parameter in assessing the quality of coffee beans. Coffee professionals use moisture meters to measure the moisture content accurately. This information helps determine the optimal roast profile and ensures consistency in the final product [20]. In summary, dehydration is a vital step in coffee production that significantly impacts the flavor development, preservation, and overall quality of coffee beans. The dehydration method, whether through sun drying, mechanical drying, or hybrid techniques, affects the chemical reactions that occur within the beans during drying. Proper dehydration ensures the formation of desirable flavors while preventing staling and maintaining acidity and body. Additionally, dehydration plays a crucial role in quality control by determining the appropriate moisture content for storage and transportation purposes. These advanced dehydration techniques, including spray-drying and freeze-drying, significantly impact the quality and shelf life of coffee. Understanding these methods is crucial for optimizing coffee production processes.

Process of Green Coffee Beans

Green coffee bean processing is a critical stage in the journey from coffee cherries to the aromatic and flavorful brew that countless individuals enjoy worldwide. The quality and attributes of the finished coffee product are determined by a number of critical steps in this process, which include the grading and sorting of green coffee beans, roasting methods, grinding procedures, and different extraction techniques. The steps are as follows:

Grading and Sorting of Green Coffee Beans

Having established the importance of dehydration techniques, the next critical step in coffee processing is the grading and sorting of green coffee beans. This stage ensures that only the highest quality beans proceed to the roasting process. It involves evaluating the quality and characteristics of the beans to ensure consistency and uniformity in the final product. The grading process typically takes place at the origin, where coffee is grown and harvested. The objective of this stage is to separate beans based on size, density, and defects. According to Tolessa et al. [22], green coffee beans are classified into different grades, such as AA, AB, or C, with the primary criterion being bean size. This grading system allows coffee producers to ensure consistency in their products and cater to specific consumer preferences. Sorting also involves the removal of defective beans, such as those with insect damage or mold, as these can adversely affect the quality of the final brew [12].

The grading of green coffee beans is primarily based on factors such as size, shape, color, density, and defects. The size of the beans is an important criterion, as it affects the roasting process and extraction efficiency. Beans are usually classified into different sizes, such as screen sizes 14, 16, or 18, with more significant numbers indicating smaller bean sizes. Illy and Viani [11] suggests that bean size affects the rate of heat transfer during roasting. Smaller beans tend to roast faster due to their higher surface-to-volume ratio, while larger beans require more time for heat penetration. This difference in roasting time can influence the development of desirable flavors and aromas. Smaller coffee particles were observed to have extracted more quickly than larger particles due to their increased surface area [23–25]. This implies that smaller beans with a higher surface-to-volume ratio may yield a more efficient extraction. Ameyu and Mechara [26] also revealed that bean size affects the sensory attributes of coffee, such as acidity, body, and sweetness. Smaller beans were associated with higher acidity and sweetness, while larger beans exhibited a fuller body.

Shape is another aspect considered during grading. Beans can be categorized as flat, peaberry (a single round bean instead of two halves), or other specific shapes. The shape can influence the flavor profile and brewing characteristics of the coffee. Irregularly shaped beans may result in uneven heat distribution during roasting, leading to variations in flavor development [27–29]. In contrast, uniformly shaped beans allow for more consistent heat transfer and roasting [25].

Beans should have a consistent color within a specific grade, indicating proper ripeness during harvesting. Green beans that are too light or too dark may indicate under or over-ripeness, respectively, which is also related to the solubility of the beans [21]. This suggests that lighter-colored beans may extract more easily during brewing, resulting in higher extraction efficiency. Farah [30] demonstrated that different roasting levels produce distinct flavor profiles. Darker roasts are bolder and more bitter, whereas lighter roasts are typically fruitier and more acidic in flavor. The final flavor profile can also be influenced by the color of the beans prior to roasting; green beans are frequently linked to vegetal or grassy aromas. Kovács et al. [31] observed that darker roasted beans produced a darker brew color compared to lighter roasts. This visual aspect can influence consumer perception and expectations regarding the taste and strength of the coffee.

Furthermore, density affects the heat transfer within the beans during roasting, leading to variations in the development of flavors and aromas. Higher-density beans have been observed to require more energy to reach the desired roast level compared to lower-density beans [32, 33]. This difference in energy requirement can be attributed to variations in heat transfer efficiency caused by differences in bean density. Higher-density beans are generally considered to have better quality due to their potential for better flavor development during roasting. Flores et al. [33] also discovered that higher-density beans exhibited higher levels of certain volatile compounds responsible for desirable flavors and aromas. These findings suggest that bean density can influence the development of specific flavor profiles during the roasting process. Furthermore, Franca et al. [27, 28] observed that higher-density beans resulted in higher extraction yields compared to lower-density beans. Moreover, Cordoba et al. [23] explored the relationship between bean density and extraction kinetics during espresso brewing. It was observed that higher-density beans required longer contact times with water to achieve optimal extraction levels. This suggests that bean density influences both extraction yield and extraction kinetics, ultimately affecting the overall flavor and quality of the brewed coffee. Cordoba et al. [23] also found that higher-density beans produced brews with more pronounced acidity and fruity notes, while lower-density beans resulted in brews with milder acidity and nutty characteristics. dos Santos Scholz et al. [34] also reported that higher-density beans were associated with enhanced sweetness, body, and overall quality in the cup. These findings highlight the influence of bean density on the flavor profile and sensory attributes of brewed coffee. Higher-density beans absorb less water compared to lower-density beans, leading to differences in extraction efficiency [35]. Furthermore, higher-density beans require coarser grinds to achieve optimal extraction levels, while lower-density beans require finer grinds [36]. This suggests that bean density influences the particle size distribution necessary for achieving desired extraction levels.

Roasting Techniques and Their Implications on Dehydration

Roasting is a transformative step in coffee processing, and it significantly impacts the dehydration of green coffee beans. The beans lose moisture, change color, and take on their distinct flavor and aroma when heat is applied during roasting. High temperatures are applied to the beans during the roasting process, which triggers chemical reactions that give the beans their distinctive smells and scents. Various roasting techniques are employed, ranging from traditional drum roasting to modern convection and conduction methods [37]. The duration and temperature of the roasting process influence the final coffee product. A shorter, lighter roast may preserve more of the bean's original characteristics. In contrast, a darker roast can yield a bolder, richer flavor but may lead to a higher loss of moisture and potential for dehydration [11]. The choice of roast profile is a crucial consideration in determining the desired cup characteristics. Also, Illy and Viani [11] found that higher roasting temperatures resulted in a more intense and bitter taste, while lower temperatures produced a milder flavor profile. Additionally, higher temperatures were linked with darker color and increased levels of certain volatile compounds responsible for aroma.

Green coffee beans typically contain a moisture content of around 10–12%, which needs to be reduced to approximately 2–4% for optimal roasting. Dehydration occurs as the heat causes the moisture within the beans to dissolve. The dehydration rate during roasting depends on various factors, such as bean size, duration, and the roasting temperature. Higher temperatures and longer roasting times result in more significant moisture loss. The rate of dehydration increases with increasing temperature and decreasing humidity [5, 38]. It was found that at temperatures above 250 °C, the dehydration rate was significantly higher than at lower temperatures [39, 40]. Additionally, the rate of dehydration was slower at higher humidity levels, indicating that moisture content plays a crucial role in the dehydration process. Also, coffee beans with higher initial moisture contents undergo a slower dehydration process [9]. This is because water molecules need to be evaporated before the beans can dry out completely. The authors suggested that controlling the initial moisture content of the beans could help optimize the roasting process and improve the final product's quality.

The type of coffee beans also influences the rate of dehydration. Arabica beans, for example, have a higher moisture content than Robusta beans and, therefore, require longer roasting times to achieve the same level of dehydration [41]. This is because Arabica beans contain more lipids and sugars, which take longer to break down and release their flavors and aromas. However, it is crucial to strike a balance between dehydration and preserving the desirable compounds within the beans. Overly rapid dehydration can lead to uneven roasting and potential flavor defects. If the moisture is removed too quickly, the outer layers of the bean may become overly dry before the interior has a chance to develop its flavors fully. This can result in a lack of complexity or even burnt flavors.

Coffee beans with higher initial moisture contents undergo a slower dehydration process [5, 42]. This is because water molecules need to be evaporated before the beans can dry out completely. It was suggested that controlling the initial moisture content of the beans could help optimize the roasting process and improve the final product's quality.

On the other hand, insufficient dehydration can lead to underdeveloped flavors and a grassy or vegetal taste in the final cup. Poltronieri and Rossi [43] stated that inadequate drying resulted in an increase in undesirable flavors, such as fermented or musty notes. These off-flavors are often associated with microbial growth and improper fermentation during drying. Also, Farah [30] observed that under-dried coffee beans had higher levels of organic acids, including chlorogenic acids, which contribute to acidity in the final cup. This increased acidity can negatively affect the taste profile of the coffee, resulting in a sour or sharp flavor. Furthermore, Ayano [44] highlighted the significance of adequate drying to inhibit the growth of mycotoxigenic fungi, which can cause the production of harmful toxins. Insufficiently dried coffee beans provide a favorable environment for fungal growth, potentially leading to health hazards and quality deterioration. It is essential to ensure that enough moisture is removed during roasting to allow for proper flavor development while avoiding excessive dehydration that could compromise the quality.

Roasters employ various techniques to control dehydration during the roasting process. These include adjusting temperature profiles, airflow, and drum speed. By carefully monitoring these parameters, roasters can achieve optimal dehydration levels while maximizing flavor development and maintaining consistency.

Grinding Processes

Grinding is a pivotal stage that occurs just before the coffee is brewed. The grinding process breaks down the roasted beans into smaller particles, increasing their surface area and allowing for efficient extraction of flavors during brewing. The degree of grinding impacts the surface area of the coffee particles, which, in turn, affects the rate of extraction during brewing. Illy and Viani [11] found that finer grind sizes resulted in higher extraction yields, indicating that more soluble compounds were extracted from the coffee grounds. Additionally, they observed that finer grind sizes led to increased acidity and bitterness in the resulting espresso. Cordoba et al. [45] found that finer grind sizes resulted in faster extraction rates. They also noted that finer grinds led to higher concentrations of certain flavor compounds, such as caffeine and trigonelline, in the brewed coffee. Coffee grinders are available in various types, including blade grinders and burr grinders (Fig. 4). Blade grinders use a rotating blade to chop the coffee beans into particles of varying sizes. In contrast, burr grinders utilize two serrated disks to create uniform particle sizes [10]. The choice of grinding method is essential for achieving consistency in particle size, as this impacts the extraction process and, consequently, the taste and strength of the coffee. For example, espresso requires a fine grind to allow for adequate

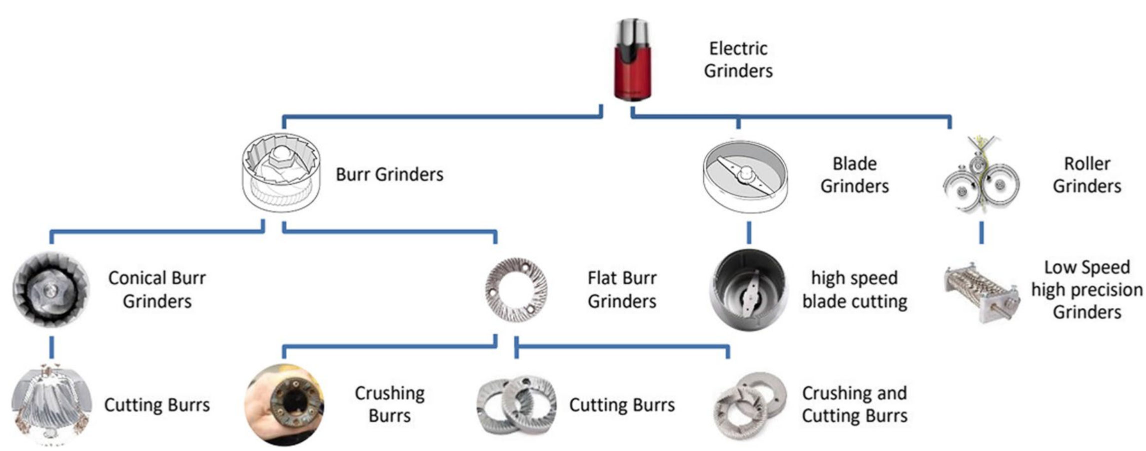


Fig. 4 Types of grinders [46]

extraction in a short period, whereas French press coffee benefits from a coarser grind for a more extended extraction period [10].

Burr grinders are considered superior to blade grinders as they offer more precise control over grind size [47]. They consist of two abrasive surfaces (burrs) that crush the beans between them. Burr grinders provide a more consistent grind size, resulting in better extraction and flavor consistency. Roller mills are often used in commercial settings for large-scale grinding operations. They utilize a series of rotating metal rollers to crush the beans into particles of uniform size. Roller mills are highly efficient and can produce large quantities of coffee grounds quickly.

Different Extraction Methods for Green Coffee

Extraction methods are the final step in the journey from green coffee beans to a cup of brewed coffee. Different methods include drip brewing, espresso, pour-over, French press, and cold brew, among others. Each method involves the controlled infusion of hot water with ground coffee, leading to the solubilization of compounds responsible for flavor, aroma, and other sensory attributes [10]. The choice of extraction method is a critical consideration for coffee enthusiasts, as it impacts the flavor, strength, and body of the coffee. Espresso, for instance, is known for its concentrated and bold taste due to the high-pressure extraction process, while cold brew results in a milder, less acidic flavor due to the prolonged steeping time. Furthermore, Classical methods such as maceration and Soxhlet extraction, as well as innovative methods like turbo extraction and ultrasound-assisted extraction, have been studied for their impact on the bioactive compounds in green coffee beans [10]. Traditional extraction practices using solvents like hexane have been effective but may not align with modern consumer expectations for greener extraction approaches. Modern extraction methods are faster, more efficient, and require less solvent, thus offering potential benefits for the quality of the extracted compounds (tech. n.d.). In addition, the heat from traditional extraction methods may alter the properties of bioactive compounds, highlighting the need for alternate techniques to harvest valuable compounds from green coffee beans (tech. n.d.). Data fusion combined with chemometrics has been effective in evaluating green coffee oil obtained by different extraction techniques. This demonstrates the importance of extraction methods in determining the quality of green coffee oil, including lipid yield, fatty acid composition, bioactive components, and antioxidant activity [48].

Comparative Analysis of Green Coffee Bean Dehydration Methods

The dehydration of green coffee beans is a critical step in their processing, affecting their shelf life and overall quality. Sun drying, although traditional, is still widely used due to its cost-effectiveness and positive impact on cupping scores. Mechanical drying methods such as hot air drying and drum drying offer more control over the process parameters, resulting in faster and more uniform dehydration. Vacuum drying, although requiring specialized equipment, provides advantages such as shorter processing times and better preservation of aroma compounds. The choice of dehydration method depends on various factors such as climate conditions, available resources, desired processing time, and desired coffee quality.

Sun Drying vs. Mechanical Drying Methods

One of the most fundamental comparisons in green coffee bean dehydration is between sun drying and mechanical drying methods. Sun drying involves spreading freshly pulped coffee beans on patios or raised beds in direct sunlight. This traditional approach is often favored for its simplicity and low cost. However, it is sensitive to weather conditions and may lead to inconsistent drying [49].

In contrast, mechanical drying methods employ technologies such as hot air convection dryers, drum dryers, or fluidized bed dryers. These methods offer better control over temperature and humidity, resulting in more consistent drying rates. Oliveira et al. [50] Highlighted those mechanical drying methods can lead to improved quality by reducing the risk of mold growth, a common issue with sun drying. It was also reported that sun drying resulted in slower moisture removal compared to mechanical drying methods but produced higher-quality coffee with better cupping scores. Qadry et al. [51] compared hot air drying with sun drying and found that the former method significantly reduced the drying time while maintaining coffee quality.

According to Qadry et al. [51], sun drying can be an effective method for reducing the moisture content of coffee cherries. During the drying process, various chemical reactions take place within the beans, contributing to the development of distinct flavor attributes. Exposure to sunlight can influence the formation of specific aroma compounds and can result in a unique cup profile. However, one of the challenges of sun drying is its dependency on weather conditions and the need for vigilant monitoring to prevent over-drying or fungal contamination.

It was observed that mechanical drying methods can significantly reduce the drying time compared to sun drying [52]. This not only improves the overall processing efficiency but also minimizes the risk of defects such as mold and fermentation. Mechanical drying is highly controllable, allowing producers to adjust temperature and airflow to achieve specific moisture content levels. However, it's crucial to monitor the process carefully to prevent over-drying, which can adversely affect the beans' quality and flavor.

Impact of Drying Temperature

The drying temperature is a critical factor that influences the flavor and aroma of the final coffee product. Drying temperatures in the range of 90 °C to 110 °C are commonly used in mechanical dryers. Higher drying temperatures can accelerate the dehydration process but may negatively affect the cup quality by causing Maillard reactions that produce undesirable flavors [53]. Lower drying temperatures, on the other hand, can preserve the coffee's intrinsic characteristics but extend the drying time. Isquierdo et al. [54] found that higher drying temperatures lead to faster moisture removal. In their experiments, they discovered that drying green coffee beans at 60 °C reduced moisture content more rapidly than drying them at 40 °C. This highlights the direct relationship between drying temperature and moisture reduction, a critical factor in preserving the beans and preventing spoilage.

In addition, Borém et al. [55] observed that higher drying temperatures, such as 70 °C, tended to produce coffee with a more pronounced roasted or smoky flavor. In contrast, lower drying temperatures, around 40 °C, were associated with a milder and more balanced flavor profile. This research underscores the importance of selecting the appropriate drying temperature to achieve the desired taste characteristics in the final coffee product. Tesfa [52] found that higher drying temperatures accelerated the breakdown of chlorogenic acids, which are vital contributors to coffee's acidity. Consequently, drying at elevated temperatures led to reduced acidity in the final coffee. This demonstrates the need for precise temperature control during drying to preserve desired chemical compounds and flavor precursors.

Fadri et al. [56] also showed that higher drying temperatures led to a decrease in overall cup quality, acidity, and aroma intensity. Additionally, higher temperatures were found to increase the levels of undesirable compounds such as furfural and acrylamide, negatively affecting the flavor profile of the coffee. In another study by Dong et al. [48], Robusta coffee beans were dried at different temperatures ranging from 40 °C to 80 °C. The researchers observed that higher drying temperatures resulted in a decrease in total chlorogenic acids content, which are essential compounds contributing to the antioxidant activity and flavor of coffee. Moreover, higher temperatures were found to accelerate lipid oxidation, leading to an increase in free fatty acids and off-flavors in the final product. The drying temperature also influences the physical characteristics of green coffee beans. Ameyu and Mechara [26] revealed that higher drying temperatures led to darker and more unevenly colored beans. Additionally, higher temperatures caused an increase in bean hardness, making them more difficult to grind and affecting the extraction process during brewing.

Furthermore, Menya and Komakech [57] found that higher drying temperatures resulted in lower moisture content, indicating a more efficient dehydration process. However, excessively high temperatures can lead to over-drying, which negatively affects the quality and flavor of the coffee. Determining the optimal drying temperature for green coffee beans is crucial to achieving desirable quality attributes. Bicho et al. [58] investigated the effect of different drying temperatures (40 °C, 50 °C, 60 °C, and 70 °C) on the sensory quality of Arabica coffee beans. The results indicated that a drying temperature of 50 °C yielded the best sensory attributes, including aroma intensity, acidity, body, and overall quality. A similar observation was also made by Oliveira et al. [50].

Parchment vs. Natural Drying

Green coffee beans are typically dried using two primary methods: parchment drying and natural drying [5]. Parchment drying, also known as wet processing or washed processing, involves removing the outer skin (cherry) of the coffee fruit immediately after harvesting. The remaining mucilage-covered beans are then spread out on raised beds or patios to dry. This method requires careful monitoring and turning of the beans to ensure even drying and prevent fermentation or mold growth. Parchment drying typically takes around 7–14 days, depending on various factors such as weather conditions and bean density. On the other hand, natural drying, also known as dry processing or sun drying, involves leaving the coffee cherries intact during the drying process. The cherries are spread out on large patios or raised beds and left to dry naturally under the sun. This method typically takes longer than parchment drying, ranging from 15–30 days.

The choice between parchment drying and natural drying depends on various factors, including the coffee variety, climate, and desired flavor profile. Parchment drying is favored for producing cleaner, brighter, and more uniform coffee profiles, as it allows for precise control over the drying process. However, it requires more resources and infrastructure to maintain the controlled environment. Natural drying is often preferred for its simplicity and lower cost, particularly in regions with ample sunshine. Nevertheless, the potential for off-flavors and the need for vigilant monitoring to prevent spoilage must be considered. Another comparative aspect of green coffee bean dehydration is the choice between drying beans in their parchment (with the outer husk intact) or drying them natural (with the parchment removed). Parchment drying is often preferred as it provides an additional layer of protection during drying and storage, which can improve bean quality. However, Tunde-Akintunde [59] notes that natural drying can lead to unique flavor profiles as it exposes beans to more direct contact with the elements.

Kathurima et al. [60] demonstrated that parchment-dried coffee beans exhibited higher levels of desirable flavor compounds such as sugars and acids compared to naturally dried beans. This suggests that parchment drying may contribute to a more complex and nuanced flavor profile in the final cup of coffee. Ameyu and Mechara [26] found that parchment drying resulted in better control over moisture content and reduced defects compared to natural drying methods. The controlled environment provided by parchment drying minimizes the risk of spoilage and allows for more precise control over the drying process. The parchment layer acts as a protective barrier, preventing direct exposure of the beans to the elements and potential contaminants [8]. Moreover, parchment drying allows for more precise control of drying times and reduces the risk of over-drying, which can adversely affect coffee flavor [5]. Natural drying can also result in longer drying times, and the beans are more susceptible to mold and fermentation due to the extended exposure to moisture and the cherry's sugars [61]. Additionally, direct contact with the fruit pulp can lead to fruity and fermented flavor notes in the final cup, which some consumers may appreciate, but it may not be suitable for all coffee varieties. Dong et al. [48] provides a comprehensive analysis of the impact of drying methods on coffee quality. The research emphasizes that while parchment drying generally results in a more consistent cup profile, natural drying can produce unique flavor characteristics that some specialty coffee consumers value. Thus, the choice between the two methods should align with the specific goals and preferences of coffee producers.

Dry Fermentation vs. Wet Fermentation

Dry fermentation and wet fermentation are two standard methods used in the dehydration of green coffee beans during the processing stage. Both methods have their advantages and disadvantages, and their suitability depends on various factors such as climate, infrastructure, and desired flavor profiles. The fermentation process also influences the drying phase. Some coffee producers prefer to dry beans immediately after pulping (dry fermentation), while others use a wet fermentation process, which includes soaking beans in water to remove mucilage. Haile and Kang [14] shows that wet fermentation can reduce the drying time and may contribute to a cleaner cup profile, while dry fermentation might result in more complex and fruity flavors. During the dry fermentation process, microorganisms present on the surface of the cherry interact with its sugars and other compounds. These microorganisms include yeasts, bacteria, and molds that contribute to the fermentation process. As a result, various enzymatic reactions occur within the cherry, leading to changes in its chemical composition. Evangelista et al. [62] found that yeasts were the dominant microorganisms during the early stages of fermentation, followed by bacteria and molds. They also observed an increase in lactic acid bacteria towards the end of the fermentation process.

The duration of dry fermentation can vary depending on factors such as temperature, humidity, and desired flavor characteristics. Typically, it takes around 15–30 days for coffee cherries to reach an optimal moisture content for storage (around 11–12%). However, this extended drying period can make dry fermentation more susceptible to external factors such as rainfall or pests.

The wet fermentation process involves the breakdown of the mucilage layer surrounding the parchment-covered beans. This breakdown is facilitated by microorganisms present in the water, primarily lactic acid bacteria and yeasts. These microorganisms consume the sugars present in the mucilage, resulting in the production of organic acids such as lactic and acetic acid. de Jesus Cassimiro et al. [63] revealed that lactic acid bacteria were dominant during the early stages of fermentation, followed by yeasts and acetic acid bacteria. They also observed that different fermentation tanks exhibited variations in microbial populations, suggesting the influence of environmental factors on microbial dynamics. Wet fermentation typically lasts for 12–48 h, depending on factors such as temperature, pH, and desired flavor profiles. After fermentation, the beans are thoroughly washed to remove any remaining mucilage before being dried either on raised beds or using mechanical dryers.

The choice between dry fermentation and wet fermentation depends on various factors such as climate, infrastructure, market demand, and desired flavor profiles. In regions with low humidity and ample sunlight, dry fermentation may be a suitable option as it utilizes natural resources without requiring extensive infrastructure. However, it is important to consider the potential risks associated with more extended drying periods, such as uneven drying or spoilage due to unfavorable weather conditions. The comparative analysis of green coffee bean dehydration methods is a complex and multi-faceted area of research in the coffee industry. It involves evaluating drying methods, temperatures, and pre-drying treatments, all of which impact the quality, flavor, and aroma of the final coffee product. Understanding these factors is essential for coffee producers to make informed decisions that align with their product goals and quality standards.

Integrative Steps in the Production Workflow One of the main apparent steps is resting, where the water activity and moisture content reach to equilibrium within the product. This is done in a special warehouse where it should be clean and insect and rodents-free. This step is essential to allow the green coffee to equilibrate in its water activity to the minimum amount possible after reaching a shallow moisture content. Any high moisture content coffee brought to the warehouse implements a spreading danger among other coffee beans that already exist in the warehouse. This place should also be as clean as possible so as not to let any threatening insects and rodents sabotage the products. Also, mentoring the temperature and relative humidity is the best choice in different environments to ensure the proper storage condition being implemented inside the warehouse.

Grading and sorting are one of the primary processes after resting. Grading is done based on the density, size, color, and many other factors. Grading helps the producers know their product very well. Also, this will let the buyer have the choice to make. Depending on the application and the purpose that the buyer wants, the grade might be selected. Grading also gives the chance to have a wide range of pricing based on the quality needed. Mechanical grading is the right approach where air blow, vibration, and fixed holes are used associated with mechanical conveyors and belts. Gravity might also be used to decrease the mechanical force needed in the operation.

Roasting is a critical process where the coffee is heated to above the boiling point of the water most of the time. Roasting participates significantly in the water removal and dehydration of the beans, which will produce very shelf-stable beans. The moisture content reduction varies from one product to another and from roasting method to another, but the essential amount is between 4–5% moisture content reduction. In some cases, the reduction can reduce the amount of water from 11 to 2% moisture content. Various roasting degrees are available today in the market depending on the consumers' choice and demand. Dark, medium, and light roast choices are available in various brands and markets. Roasting temperature can be very high, as high as 200 ℃ in some cases, with continuous motion (rotating) of the beans to facilitate even temperature distribution and not to burn the coffee. This is a batch operation where the coffee is fed into a large-scale roaster 100 s of kilograms on an industrial scale to a few kilograms in the house kitchen.

Milling the roasted coffee is an optional choice at this stage, but many brands and companies sell roasted coffee instead. Some claim that the grinding and crushing of the coffee beans will eventually release most of the aroma and flavor. Therefore, consumers do like roasted coffee over ground coffee. However, other consumers might even prefer green coffee that they can roast and grind at their leisure at home.

Process of Instant Coffee

The history of instant coffee, also known as soluble coffee, dates back to 1771 in the United Kingdom, but it wasn't until 1890 in New Zealand that it received a patent [64]. The popularity of instant coffee is driven by its convenience, as seen in the increased sales of capsule coffee machines [65]. For many non-coffee-drinking cultures, particularly in Eastern Europe and East Asia, instant coffee serves as the primary introduction to coffee consumption, with a significant demand for 3-in-1 beverages [66]. Many consumers prioritize speed over taste, seeking a quick caffeine fix, especially at home [65]. All of that has led to a great global instant coffee market valued at USD 13.5 billion in 2022, which is projected to grow to USD 21.49 billion by 2031 [67]. In today's fast-paced society, the practicality of instant coffee continues to drive its consumption, along with improvements in quality.

Instant coffee undergoes three main processes: roasting, milling, and brewing. Blending also might be desired sometimes. Percolation (brewing) coffee is a unique process that should be taken care of very carefully before the coffee extract is about to be formed. Percolation is dependent on the density, roasting, temperature, and properties of the coffee [39, 40]. Also, too much water might make the drying very difficult. Therefore, a balanced operation should be maintained.

Another drying stage is required for the instant coffee when the coffee is already concentrated. Coffee extraction is dried by either a) spray-drying, removing water by evaporation in a hot air current, or b) freeze-drying, water is frozen and vacuumed to sublime the ice with a small amount of heat, low temperature. The concentrated coffee extraction has 25% concentrated solid weight to weight base. This is might vary depending on the type of drying and conditions of drying. These types of drying do add to the cost of the coffee price where it is usually higher than the roasted and milled coffee blend.

Grading, Roasting, and Grinding

Various factors are involved in grading the coffee beans depending on the region that produces this commodity. Grading helps to price the coffee bean fairly according to the buyers' rules and regulations. Automation makes the rules somewhat not fixable enough in term moving the bean from one place to another, such as conveyor belts or pumping through close tubes. Most popular methods of grading based on size, defects, or color. Also, moisture content is important where it must reach a certain range (below 12%). Five grades or categories are assigned by number from grade 1 (no defects in the bean itself) to grade five when beans do contain a significant number of defects express in percentage (e.g., grade one 0–3% and grade five more than 86% of the beans do have defects) [68].

Roasting, on the other hand, depends on the heat transfer (conduction and convection) associated with beans motion inside the roaster. Traditionally, green coffee beans are roasted at 180–230 ºC for 12–15 min. Coffee beans' tissue structure changes at 50 ºC, leading to protein denaturation and increased water evaporation with higher temperatures. Browning of beans occurs at temperatures above 100 ºC through a number of reactions. About 150 ºC, gaseous compounds are produced, resulting in increased bean volume. At 180–200 ºC, disrupting the endosperm causes bean shattering, bluish smoke, fragrance, and caramelization. To avoid excessive browning and aroma loss, coffee beans are taken from the roasting chamber and quickly chilled with a stream of cold air or water spray [69–72].

Elevating the beans temperature to the desired roasting temperature usually takes from a few minutes up to 22 min [73], depending on the interior design of the roaster, coffee beans motion (rpm), beans geometry, moisture content, desire roasting temperature, and air flow inside the roaster since both conduction and convection heat transfer are involved. One of the byproducts in this process is the high moisture, air (exhaust) and some of the parchment that came attached with coffee beans. Roasted coffee beans were classified into four levels: light coffee, medium coffee, medium-dark coffee, and dark coffee. each level of coffee roasts beans had color gradation, thus there were more varieties of coffee roast beans [74]. Figure 5 illustrates those coffee beans grades, where the coffee beans are categorized into four main groups with acidity and bitterness indicators. It should be noted that the fluidized bed also can be used to roast the coffee beans since their geometry is somewhat round and uniform in shape. Also, rotating cylinders containing the green beans and hot combustion gases are commonly used in most roasting plants. This equipment ensures even roasting of the beans [75].

Grinding is a mechanical means of crushing the beans to a small fine or coarse powder with larger particle size. After roasting, the beans are rapidly cooled down to around 40 °C before being finely ground into powder using an industrial grinder. The grinding process releases a large amount of aroma into the air [75]. To minimize the loss of aroma during grinding, nitrogen gas is pumped through the ground coffee to collect the aromas, which are then stored in a tank. The collected aroma will be added back to the coffee later in the production process. The industrial process requires a certain level of particle powder size depending on the brewing and filtration system. This also governs the brewing efficiency and the coffee extraction. The surface of the powder plays role in the extraction process. Very fine powder such as espresso grinding, or Turkish coffee might be difficult for the system to take in. The particle size can be ranging from 1.5 to 0.38 mm with a total area of 32 to 128 cm2/g, whereas the whole bean has a size of 6 mm and a total area of 8 cm2/g depending on the type of the coffee [39, 40]. Today, the size chart has expanded based on the desired applications where seven levels of milling are available. That starts from coarse with three levels (extra-coarse, coarse, and medium-coarse) from the largest to the smallest. Medium is also produced as well as three level of fine powder (medium-fine, fine, and extra fine). The desired size in percolation in industrial level would be around 1.4–1.5 mm as referred to regular grinding in some text. The particle size will be also considered after dehydration since it is important for solubility and other aspects.

Brewing

Brewing or sometimes referred to as percolation is the infusion of hot water in the ground coffee to extract the aromatic and organic compounds from the coffee ground at approximately 100 °C and 101.3 kPa. The ground coffee is brewed using extraction equipment, where steam and water are applied to make brewed coffee. The brewed coffee is then heated in an evaporator at 70 °C until it is condensed by 50% into an extract. Similar to the coffee maker at home, industrial percolation has larger quantity but also performed at a slightly higher pressure and temperature sometimes. The reason that higher working pressure and temperature would be because of the higher efficiency, and higher extraction

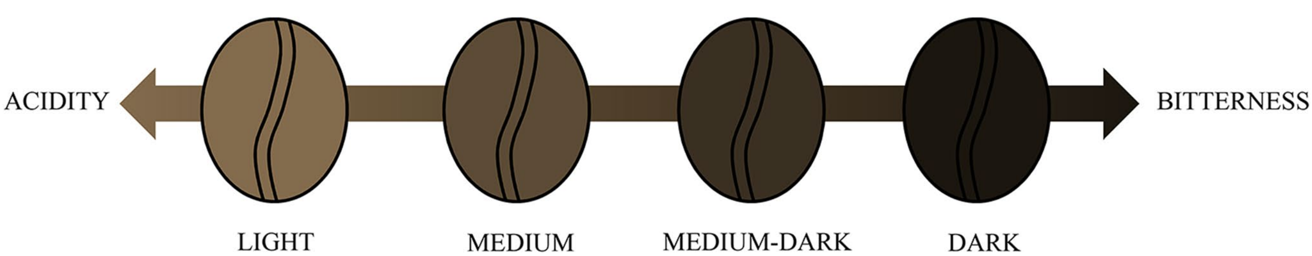


Fig. 5 Roasting grades for the beans

percentage of the desired compounds (solid content from 36–46%). Cold brewing is also available with slightly higher pressure (17 °C and 338 kPa). Higher yield of solid content could be reached by percolation at 200 °C and 1500 kPa. The latter would be higher capital cost operation, but also effective in extracting more volatile compounds [76].

Extraction Methods Tailored to Instant Coffee

The brewed coffee must be in a concentrated form which is called extract or slurry. The solid content should be increased from, for example, 22% to as high as 64%. This involves water activity reduction and high amount of water vapor extraction. Usually, to avoid the high capital cost of the operation vacuum evaporation is applied where the temperature (energy) can be reduced. The latent heat of evaporation is very high so that is the reason for applying a vacuum in addition to the temperature which will make the process feasible and inexpensive. The solid content varied in the slurry depending on the process applied. The spray drying can take lower solid content than the freeze-drying that is because of the high atomizer pumping speed and higher temperature applied in spray drying while solid content in freeze drying can be concentrated to a certain degree due to lower working temperature and slow evaporation process. In both cases, the process parameters dictate the balance of solid content and optimization must be considered.

The evaporation process is undertaken in evaporators where the design varies greatly depending on the product, the capital investment, and production capacity. There are two main types (raising and falling films), and there is more than one configuration which includes tubes, plate, etc. it should be mentioned that the evaporator could be single or multiple-effect where series of evaporators are in line to process the concentrate.

The extract must be preheated for the spray-drying process to be ready for evaporation while it is the opposite for freeze-drying the extract should be cooled down. In spray drying the pressure and feeding capacity is very high, therefore, the pumping would be high. This will be considered in the spray drying section. Freeze drying, on the other hand, can be optimized and relatively lower than the spray drying speed where the conveyor that conveys the extract must ensure the freezing of the coffee slab. In the following sections, the spray-drying technique will be explained in detail first and then freeze drying.

General Foods and Nestle are using multi-stage extraction that varies in temperature start low and end with high temperature up to 200 °C. The conventional battery works as countercurrent reach up to 220 °C. However, in most cases, extraction at 100 to 120 °C with atmospheric pressure is done which costs less and have a mild effect on the coffee quality [77], but the efficiency is low.

The production of instant coffee involves several steps, including extraction, concentration, drying, and packaging. Extraction is a crucial step in the production process as it determines the quality and flavor profile of the final product. Various extraction methods have been developed and tailored specifically for instant coffee production.

Spray Drying Method

The spray drying method is the most commonly used extraction technique in the production of instant coffee. It involves the conversion of liquid coffee extract into a dry powder form through rapid evaporation. The process begins with the extraction of soluble compounds from roasted coffee beans using hot water or steam. The resulting liquid extract is then concentrated to increase its solids content. Subsequently, the concentrated extract is atomized into fine droplets and sprayed into a hot drying chamber (Fig. 6). The droplets quickly lose moisture and solidify into small particles, which are then collected as a dry powder.

The steps of spray-drying can be summarized in the following points:

- Formation of the droplets (by a nozzle)
- Hot and dry air supplied 269 ℃ [39, 40]
- Recovery of the fine powder (coffee)
- Recovery of the moist air with reduced temperature.

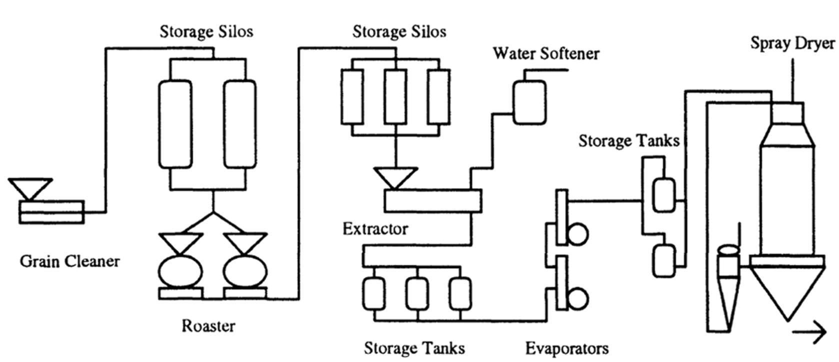


Fig. 6 Diagram of the process of instant coffee, adapted from [81]

In some literature the last two points are called separation [78]. The most important futures in spray drying are the extract, atomizer, and the way of separation of product from the moist air. In the instant coffee, drying extract might vary in the solid that contains from 15 to 25% w/w. The final dried droplets might vary in diameters from 200 to 300 µm [78] with moisture content of about 2–3% [39, 40]. In general, atomizers available depend on the centrifugal, pressure, kinetic, or sonic energy to spread the extract at various pressure ranging from 700 to 1000 kPa [79]. The widely-used atomizers are the pressure and rotary (two fluid and single fluid nozzles are used, too). It is also a critical point in designing the spray dryer that the inlet air temperature should be about 250 ℃ and outlet air temperature is about 110 ℃ [80]. The instant coffee extract is starting with water activity of 0.95 [78], and this is reduced greatly in spray drying. The final moisture content varies from product to another which is about 2–8%. It is believed that the extract concentration will affect the particle size at the end of the process. Next a very typical flowchart for instant coffee in coffee plant.

Figure 6 shows the process that the instant coffee undergoes in plant before spray-drying. This is also showing roasting extraction, and evaporation of making the concentration.

The quality of instant coffee produced by spray-drying is influenced by various factors, including the initial coffee concentrate composition, drying conditions, and post-drying treatments. Studies have shown that spray-drying can lead to changes in the chemical composition of coffee, such as the degradation of certain flavor compounds and the formation of Maillard reaction products. However, when properly optimized, spray-drying can produce instant coffee with acceptable sensory attributes and overall quality. Research has shown that spray-drying can significantly affect the quality of instant coffee. One study found that the spray-drying process can cause the formation of undesirable compounds, such as furanones and pyrazines, which can negatively impact the taste and aroma of the coffee [82]. Additionally, spray-drying can result in the loss of volatile compounds, which can lead to a decrease in the coffee's flavor and aroma [78].

However, not all spray-drying methods are created equal. Some studies have shown that the use of a high-pressure nozzle can lead to a more uniform distribution of droplets, resulting in a higher-quality instant coffee [83]. Additionally, the use of a low-temperature drying process can help preserve the coffee's flavor and aroma [78].

The spray drying method offers several advantages for instant coffee production. It allows for high production rates, efficient removal of moisture, and preservation of aroma compounds. Additionally, it enables the customization of particle size distribution and solubility properties to meet specific consumer preferences [78, 79].

The main disadvantage in spray drying of coffee is believed to be the loss of aroma and flavor stated by both authors [39, 40, 78]. The high temperatures involved can cause evaporation of these delicate compounds, leading to a loss of aroma intensity in the final product. Furthermore, spray-drying can result in particle agglomeration and uneven drying if not properly controlled, affecting the solubility and sensory attributes of the instant coffee. Also, a further treatment is needed for instant coffee to have a larger size of particles about 1400 µm. This treatment is called agglomeration mentioned by Ghirişan and Miclăuş [78] as an essential step in spray drying for instant coffee. To boost the aroma and flavor of the spray dried coffee very small percent 5% of freeze-dried coffee might be added [39, 40]. Also, to avoid some of the drawbacks of the spray-drying, freeze-drying is used.

Freeze Drying Method

The freeze-drying method, also known as lyophilization, is another widely employed extraction technique for instant coffee production. This method involves freezing the liquid coffee extract at extremely low temperatures and subsequently removing the ice crystals through sublimation under vacuum conditions. The process begins with the extraction of soluble compounds from roasted coffee beans using hot water or steam, similar to the spray drying method. The resulting liquid extract is then frozen at temperatures below -40 °C (-40°F) to form a solid matrix. Subsequently, the frozen extract undergoes sublimation, where ice crystals directly transition from the solid state to vapor without passing through the liquid phase. The remaining freeze-dried coffee is collected as a porous and lightweight powder.

Studies have shown that freeze-drying can preserve the sensory attributes of coffee better than spray-drying. The lower temperatures used in freeze-drying help retain volatile aroma compounds, resulting in a more aromatic cup of instant coffee. Additionally, freeze-dried coffee often exhibits improved rehydration properties compared to spray-dried coffee due to its porous structure. Also, it preserves the delicate flavor and aroma compounds present in the coffee extract due to the low temperatures involved. It also results in a highly soluble and rehydratable product with a longer shelf life compared to other extraction methods [78]. The fact that the freeze-drying is performed under vacuum reduces the reaction that involves oxygen and food components. Also, reduced processing temperature of about 30 to 60 ℃ helps to have a better quality of final product. Freeze dried instant coffee, in particular, preserve the coffee aroma and nutrition values and it is practiced in industrial scale, nowadays. This technique also can be used for both solid and liquid foods.

The coffee extract by freeze-drying is believed to be having higher solid content than the spray-drying which is somewhat in 35–40% solids w/w [84]. Unlike spray-drying, freeze-drying produces fairly stable granule size. The mechanism of freeze-drying start by freezing the coffee extract from the range of -20 to -50 ℃. In specific terms, up to -30 ℃ is very sufficient freezing temperature to freeze all water within the coffee concentration [78]. The frozen coffee granule is taken to the vacuum chamber where the temperature is increased above room temperature and below the boiling point of water. The absolute pressure in the drying chamber should be maintained at least at 0.620 kPa [85]. In this step, the sublimation is occurring at relatively low temperature 30 to 60 ℃. The main disadvantage of the freeze-drying is the high cost of operation where freezing and vacuum are needed and they add on the capital cost of the operation.

One of the key factors affecting the quality of freeze-dried instant coffee is the preservation of its volatile compounds, which contribute to its aroma and flavor. Several studies have investigated the effect of freeze drying on the retention of volatile compounds in coffee [84]. The preservation of volatile compounds during freeze drying is influenced by various factors, including freezing rate, pre-freezing conditions, and drying parameters [78]. Slower freezing rates usually resulted in higher retention of volatile compounds, suggesting that controlling the freezing process can help improve the quality of freeze-dried instant coffee [78]. In addition to volatile compounds, other quality attributes such as color and solubility can also be affected by freeze drying. Freeze-dried coffee has been found to exhibit better color stability and higher solubility compared to other drying methods [78, 84]. This indicates that freeze drying can help maintain the visual appeal and functionality of instant coffee. Furthermore, Malik, Gouseti and Bakalis [86] found that freeze-dried coffee had a more porous structure, which facilitated faster rehydration compared to other drying methods. This suggests that freeze drying can contribute to the desirable texture and rehydration characteristics of instant coffee.

In terms of quality, freeze-drying produces a higher-quality final product compared to spray-drying. The slower drying rate and lower temperatures used in freeze-drying help to preserve the flavor, aroma, and nutritional content of the coffee. However, freeze-drying is a more expensive method, and the equipment required is more complex and requires more maintenance. Spray-drying, on the other hand, is a faster and more cost-effective method, but it can result in a lower-quality final product with inconsistent flavor and aroma. both spray-drying and freeze-drying are widely used methods in the production of instant coffee. While spray-drying is a faster and more cost-effective method, freeze-drying produces a higher-quality final product with better flavor, aroma, and nutritional content. The choice of drying method depends on the desired quality and cost of the final product.

Agglomeration Method

The agglomeration method is a post-extraction technique used in conjunction with either the spray drying or freeze-drying methods to improve the solubility and sensory attributes of instant coffee. After the initial extraction and drying steps, the resulting coffee powder is subjected to agglomeration, which involves the formation of larger granules by combining smaller particles together. Agglomeration can be achieved through various mechanisms, including steam treatment, fluidized bed processing, or mechanical means. Fluidized bed agglomeration, involving suspending fine coffee particles in air and applying a liquid binder, improves solubility, dispersibility, and sensory attributes [87]. Drum or pan agglomeration, achieved through tumbling and binder application, enhances flowability and bulk density, making packaging and consumption more convenient. Spray congealing, an innovative method using a spray nozzle to cool molten concentrate, results in uniform, non-dusty, and easily rehydratable coffee granules. These techniques collectively elevate the overall quality and market value of coffee products, providing consumers with an improved experience. The agglomeration process enhances the solubility of instant coffee by increasing its surface area and reducing bulk density. It also improves the sensory attributes, such as mouthfeel and aroma release, by modifying the physical structure of the particles [88]. Anandharamakrishnan [84] compared different agglomeration techniques, including freeze drying, spray drying, and fluidized bed drying, and their impact on solubility. The results indicated that freeze-dried instant coffee exhibited higher solubility compared to spray-dried and fluidized bed dried samples. This finding suggests that the agglomeration method can significantly affect the solubility of instant coffee.

In addition, Ghirişan and Miclăuş [78] revealed that freeze-dried instant coffee exhibited a more complex aroma profile with higher levels of desirable volatile compounds compared to spray-dried samples. This suggests that the agglomeration method can influence the aroma and flavor characteristics of instant coffee. Agglomeration methods can influence the particle size distribution by controlling the size and morphology of the agglomerates [89]. It also enhances flowability and dispersibility by forming larger granules, improving solubility, reducing dustiness, and enhancing sensory attributes of coffee instant powder [48, 87, 90]. The color and appearance of instant coffee are important factors influencing consumer perception and acceptance. This method can affect these attributes by altering the surface properties and structure of the coffee granules [9].

Aroma Recovery Aroma recovery usually follows the percolation process, where heat exchangers are used to cool down the steam coming from the brewing process. It should be mentioned that the target is short extraction time with low temperature to retain as much as possible of the aromatic and volatile compounds such as 4-vinyl guaiacol, 4-ethylguaiacol, 2-ethyl-3, 5-dimethyl pyrazine, guaiacol, and 2,3-diethyl-5-methylpyrazine [91]. In a broader term, the aroma recovery consists of two main steps i) is collecting the aroma, ii) depositing the aroma in the instant coffee in further steps. In the early days, the collected aroma is encapsulated in edible gum or molten carbohydrate where they are added to the powder later in the line [92]. Now infusion process during the agglomeration might be possible.

Filtration and Byproducts Byproduct form the extraction step is called spent coffee. This unwanted commodity is valuable in other processing lines such as biofuels and conversion techniques where the waste can be used in a useful method. Recycling of the extracted cake (spent coffee) second time can optimize the process of extraction. Two main outcomes of the extraction process which are the cellulose and hemicellulose. These two byproducts can be utilized in many other applications including paper pulping, nitrating, hydrolysis, and biodegradation by enzymes, whereas the hemicellulose can be used in fermentation to produce lactic acid, ethanol, hydrolysis, and biodegradation. Many applications of the waste spent coffee can be assigned to the extracted waste [4]. In addition, using this spent coffee maximize the energy consumption and minimize the environmental impact/issues which will be discussed in a separate section later in this review.

Blends and Mixtures One of the main important concepts in the coffee industry is blending the variety of beans to reach the desired quality forming a nice mixture of aroma and caffeine. This is a market-driven demand for the roasted beans. However, the same blending for the same purpose is done in instant coffee, where freeze-dried granules are mixed with spray dried agglomerates. This is done when the aroma recovery is not sufficient. The blending of two dried methods powders can be challenging because the powder is not the same in the physical properties starting from the density ending with the color difference of the powder. Freeze dried powder lighter in color and dense compared to spray dried. Table 1 shows different properties for different coffee forms.

Mass and Heat Balance To understand the two drying techniques (spray and freeze drying) mass and heat balance studies are essential. Spray-drying and freeze-drying are both highly effective processing technologies in water removal. Therefore, optimization of the process would be an efficient way of studying these parameters. For example, freezing might not be sufficient for removing all ice crystals that are attached to the coffee structure unless it is porous enough to get all water crystals out. Thus, another freezing step might be necessary sometimes. Another example, in spray-drying, reduction of operation cost 10–15% might be established by second spray-drying in the row which exists today. Whenever, it comes spray-drying or freeze-drying a heat and mass balance study is present [39, 40, 78, 80]. Knowing that the "energy can be neither created nor destroyed" [95]. The following equations might be helpful in term of mass and heat balance.

The following equation is for the mass balance:

$$m_{f1}w_{f1} + m_{a1}w_{a1} = m_{f2}w_{f2} + m_{a2}w_{a2} \ldots \tag{1}$$

Where: m_{f1} and m_{f2}: Mass flow rates of fluid at points 1 and 2, respectively. w_{f1} and w_{f2}: Mass fractions of a particular component in the fluid at points 1 and 2, respectively. m_{a1} and m_{a2}: Mass flow rates of another stream (e.g., air) at points 1 and 2, respectively. w_{a1} and w_{a2}: Mass fractions

Table 1 Coffee properties in solid and liquid form

Properties	Form	Numbers	Reference
Thermal Conductivity k	**Extract 25%**	**0.033 W/m K**	[80]
Sublimation temperature (T_{sub})	**Extract**	**-23 °C**	[80]
Permeability (10^{-9} kg/m S μmHg)	**Extract 20%** **Extract 30%**	**4–8.6** **3**	[80]
Collapse temperature	**Extract**	**-20 to -26 °C**	[80]
Bulk density (moisture content)	**Ground and roasted** **Instant** **Freeze-dried $a_w = 0.2$** **Spray-dried $a_w = 0.2$**	**330 kg/m^3 (7%)** **470 kg/m^3 (NA)** **234 to 243 kg/m^3** **194 to 243 kg/m^3**	[93] [94]
Ignition temperature (explosibility)	**Roasted**	**MEC 85 (g/m^3);** **MIE 0.16 (J);** **Cloud 720 and layer 270; and limiting O_2 concentration C17**	[93]

of a particular component in the other stream at points 1 and 2, respectively. The following equation is for the energy balance:

$$m_{f1}H_{f1} + m_{a1}H_{a1} = m_{f2}H_{f2} + m_{a2}H_{a2} + q \ldots \quad (2)$$

Where H_{f1} and H_{f2}: Enthalpies of the fluid at points 1 and 2, respectively. H_{a1} and H_{a2}: Enthalpies of the other stream at points 1 and 2, respectively. q is, the energy lost (or gained, depending on the sign convention) in the system and H is illustrated next:

$$H_{f1} = Cp\Delta T + w_{f1}Cp(of\ water)\Delta T$$
$$H_{a1} = Cs\Delta T + w_{a2}H_l$$

Where: C_p: Specific heat capacity of the fluid. C_p(water): Specific heat capacity of water. ΔT: Temperature difference. C_s: Specific heat capacity of the other stream (e.g., solid). H_l: Latent heat associated with a phase change or a specific reaction. These energy and mass balance equations can be applied on both spray and freeze drying. However, another concept of latent heat is taken into consideration in freeze-drying when the sublimation is taken place.

Strategies for Optimizing Dehydration Processes The optimization of dehydration processes is essential to ensure efficient and consistent drying, which directly impacts the flavor, aroma, and overall quality of the final coffee product. There are several strategies that can be employed to optimize dehydration processes in coffee manufacturing. One strategy is to use advanced drying technologies, such as vacuum drying or freeze drying, which can help to preserve the flavor and aroma of coffee beans more effectively than traditional drying methods [84, 96]. Another strategy is to carefully control the temperature and humidity levels during the dehydration process to prevent over-drying or under-drying of the coffee beans [96].

One of the key strategies for optimizing dehydration processes is the precise control of drying parameters such as temperature, humidity, and airflow. Research studies have shown that these parameters significantly influence the drying rate, moisture content, and quality attributes of coffee beans during the dehydration process [48, 97]. Higher drying temperatures (around 60–70 °C) have been found to result in faster drying rates but negatively affect the sensory attributes of the coffee, leading to a decrease in cup quality [48].

On the other hand, lower temperatures (around 40–50 °C) preserved the sensory characteristics but prolonged the drying time. Also, Villegas-Santiago et al. [98] found that higher airflow rates improved heat transfer efficiency and reduced drying time without compromising the sensory attributes of the final product. Pre-drying treatments are another set of strategies employed to optimize dehydration processes in coffee manufacturing. These treatments aim to prepare the beans for efficient drying by reducing their initial moisture content or modifying their physical structure.

A study by Scholz et al. [99] investigated the effect of different pre-drying treatments on the drying kinetics and quality attributes of coffee beans. The researchers compared the traditional sun-drying method with two pre-drying treatments: hot air drying and osmotic dehydration. They found that both pre-drying treatments significantly reduced the drying time and improved the sensory attributes of the final product compared to sun-drying alone. Furthermore, Cano Suárez, Ciro Velásquez and Arango Tobón [96] explored the impact of mechanical pre-drying treatments on coffee bean drying. The researchers investigated the use of centrifugation and vibration techniques to remove excess surface moisture from the beans before the main drying process. They observed that these mechanical treatments reduced the drying time and improved the overall quality of the coffee beans.

Novel Drying Technologies Advancements in technology have introduced novel drying methods that offer potential benefits for optimizing dehydration processes in coffee manufacturing. These technologies aim to enhance drying efficiency, reduce energy consumption, and preserve the sensory attributes of coffee beans. The application of infrared radiation as a novel drying technique for coffee beans have been studied [9]. The infrared radiation was reported to significantly reduced the drying time while maintaining the sensory characteristics of the final product. This technology offers a promising alternative to conventional drying methods, particularly for large-scale coffee processing. It also offers the advantage of providing heat without raising the inside temperature of the material, making it a potential method for preserving the quality and bioactive components of coffee beans during the drying process [100]. Barbin et al. [101] highlighted the reliability of infrared spectral techniques compared to traditional analytical methods, indicating the potential for using infrared radiation in coffee processing to maintain quality and composition.

Another innovative approach is vacuum freeze-drying, which involves freezing the coffee beans and then subjecting them to a vacuum environment to remove moisture through sublimation. This method preserved the volatile compounds responsible for aroma and flavor, resulting in a superior cup quality compared to traditional drying methods [102]. A patent disclosed vacuum freeze-dried green coffee beans and a processing method thereof, indicating the potential of this technique in coffee processing [103]. In addition, Silva and Schmidt [104] showed that the use of vacuum freezing in the first stage of a lyophilization cycle can increase the drying rate of coffee extract, indicating the potential of this technique in coffee processing. The combined microwave vacuum drying (MVD) method has also shown potential as a drying method for coffee beans, with the shortest drying time and lowest energy consumption [105]. The MVD has also been found to have to prevent deterioration of coffee and other agricultural products and can be an efficient and economic drying method [90, 105]. A comparative study of experimental results obtained during the drying of coffee beans using microwave and conventional oven radiation reported that microwave-based drying was faster. The processing time was reduced significantly, and diffusion coefficients of microwave-dried grains were higher compared to those dried using conventional methods [97].

Generally, the combined drying method has shown potential in preserving the quality attributes of green coffee beans, preventing deterioration, and reducing processing time. These methods have demonstrated efficiency and economic advantages, making it a promising technique for coffee bean drying. Additionally, they have shown potential to preserve bioactive components and aroma, making it a viable alternative to traditional drying methods [106].

Relationship Between Dehydration and Product Quality, Efficiency, and Sustainability The dehydration process has a significant impact on the quality, efficiency, and sustainability of coffee manufacturing. As previously mentioned, dehydration helps to preserve the flavor, texture, and aroma of coffee beans, which directly affects the quality of the final product [8]. Moreover, dehydration also helps to prevent the growth of mold and bacteria, which can negatively impact the taste and shelf life of coffee [84, 96]. Cano Suárez, Ciro Velásquez and Arango Tobón [96] found that sun drying, a common traditional method, resulted in higher levels of defects and lower cup quality compared to mechanical drying methods. The authors concluded that mechanical drying techniques such as hot air drying or drum drying can provide better control over the drying process, leading to improved product quality.

Furthermore, Alves et al. [9] demonstrated that slow drying at low temperatures resulted in superior cupping scores compared to fast drying at high temperatures. This suggests that careful control of dehydration conditions can positively influence the sensory attributes of coffee, such as acidity, sweetness, and aroma. Additionally, optimizing dehydration processes can lead to increased efficiency in coffee manufacturing, as it can reduce the time and energy required for the drying process [107]. Alves et al. [9] investigated the energy consumption of different coffee drying systems and found that solar dryers combined with heat recovery systems were more energy-efficient compared to traditional sun drying methods. Solar dryers utilize renewable energy sources and can significantly reduce greenhouse gas emissions associated with coffee processing. Moreover, Ekezie et al. [108] explored the use of innovative drying technologies, such as microwave-assisted drying and vacuum drying, to enhance the efficiency of coffee dehydration. These methods demonstrated faster drying rates and reduced energy requirements compared to conventional drying techniques.

Finally, sustainable dehydration practices can help to minimize waste and reduce the environmental impact of coffee manufacturing [8, 84]. Implementing water-saving strategies, such as using recirculation systems or adopting dry processing methods, can help reduce water usage and promote sustainability. Furthermore, Faleeva and Zaichenko [109] explored the potential of using coffee husks and parchment as biomass for energy production. By converting waste into a valuable resource, this approach contributes to the circular economy concept and enhances the sustainability of coffee manufacturing.

Quality Control and Assurance Measures Quality control and assurance play a crucial role in ensuring that coffee products meet specific standards and requirements while minimizing negative environmental impacts. These measures encompass various aspects of coffee manufacturing, including raw material selection, processing techniques, packaging, and storage. The Specialty Coffee Association (SCA) has established comprehensive guidelines for quality control in the coffee industry [110]. These guidelines cover sensory evaluation methods, green coffee grading protocols, and quality management systems. By adhering to these standards, coffee manufacturers can consistently produce high-quality products while minimizing waste and resource consumption. The importance of selective harvesting, where only ripe coffee cherries are picked, and the impact of altitude, climate, and soil conditions on coffee flavor profiles has been emphasized [111, 112].

In terms of processing techniques, proper post-harvest practices are essential for maintaining coffee quality. The wet processing method have been found to resulted in higher cupping scores and better sensory characteristics compared to dry processing [113, 114]. Implementing appropriate processing techniques not only ensures product quality but also reduces the environmental impact associated with coffee manufacturing. Additionally, innovations like eco-friendly pulping and fermentation techniques contribute to sustainable and high-quality coffee production [43]. Scientific advancements in sensory analysis and cupping protocols have enabled precise evaluations of coffee quality. Studies detail the development of standardized cupping forms, aroma wheels, and flavor lexicons to ensure consistent and accurate evaluations by professional tasters and coffee graders [115–117]. In addition, automation in sorting and grading processes, coupled with advancements in artificial intelligence, has enhanced the efficiency and accuracy of quality control measures, particularly in large-scale production [118, 119]. The impact of traceability and certification programs on the assurance of coffee quality has also been studied. Both Mendez et al. [120] and Wahyudi et al. [121] reported how certifications such as Fair Trade, Rainforest Alliance, and organic standards contribute to sustainable and ethically produced coffee, meeting the demands of conscientious consumers. This, thereby promote competitiveness in the coffee quality and prices. Furthermore, insights into optimal packaging materials, preservation of freshness, and mitigation of flavor degradation during storage contribute to maintaining coffee quality from production to consumption [122–124].

Also, understanding consumer preferences and perceptions is integral to ensuring the success of quality control measures. Studies have shown that the main factors influencing coffee consumption are sensory quality (flavor and aroma), functional aspects (stimulating effects), and habits of consumers [65, 125]. Additionally, the quality and flavor (taste and aroma) of the coffee, as well as consumer habits, are identified as the most important factors affecting the purchasing of coffee [65]. Other factors such as price, brand, friends' opinions, and the features of coffee, including origin, acidity, strength, or degree of roasting, are considered less important by consumers [125]. As the coffee industry evolves, ongoing studies will continue to shape the landscape of quality control, driving innovation and sustainability in coffee production.

Characteristics of Coffee Powder Coffee powder is a pivotal ingredient in various food and beverage products, and its characteristics significantly influence product quality and functionality. Key attributes of coffee powder include particle size distribution, surface area, moisture content, and fat content. An ideal particle size range of 10–50 µm ensures optimal performance [126, 127]. Coffee powder's surface area, which grows with fineness, impacts its capacity to absorb flavors and aromas [126]. Pure coffee powder is light in weight, has a relatively uniform porosity, smoothness, and is not sticky or lumpy [128]. It is finer and smoother compared to powder of cereal grains, such as soybeans and corns, which may have uneven smoothness and be easier to clot [8, 129]. The particle size affects the brewing process, with finer particles often leading to stronger, more intense flavors in espresso, while coarser grinds are suitable for methods like French press [5]. Moreover, moisture content, ideally between 10 and 12%, is vital for shelf life and stability, while an ideal fat content between 1 and 2% is crucial for performance [39, 40, 130]. Raw coffee beans with moisture above 13% or below 9% may not maintain quality and could be rejected [8].

It has a pleasant aroma, a slight bitterness, and typical deep sour acidity. Furthermore, the flavor characteristics of coffee powder are primarily determined by the coffee used to produce the powder. This profile is a key characteristic, with different types of coffee powder capturing the particular flavor characteristics of special roasts or varieties of coffee. Espresso powder, for example, captures the flavor of espresso and is often used in baking or candy making. These characteristics collectively define the utility and quality of coffee powder in a range of applications. Understanding these characteristics empowers coffee enthusiasts to tailor their brewing methods, bringing out the nuanced flavors and ensuring a delightful and personalized coffee experience.

Comparative Study of Green Coffee Beans and Instant Coffee Green coffee bean processing and instant coffee manufacturing represent two distinct stages in coffee production. The former involves a series of key stages starting with harvesting, sorting, and cleaning coffee cherries, followed by depulping, fermentation, washing, drying, hulling, sorting, and grading, and concluding with the pivotal roasting process, which imparts the beans with their characteristic flavors and aromas [14]. On the other hand, instant coffee manufacturing takes a different route, beginning with the extraction of soluble compounds from roasted coffee beans through methods like brewing or percolation [131, 132]. The next steps involve concentration to enhance the flavor and aroma, followed by drying, with methods like freeze-drying or spray drying [8, 23]. An optional agglomeration step can also be included, wherein the dried particles are made to adhere to one another to form larger granules [133]. Finally, the instant coffee is packaged into various consumer-friendly forms, such as jars, sachets, or single-serve packets [5].

These comparative analyses reveal that while green coffee bean processing focuses on preserving and enhancing the natural qualities of coffee, instant coffee manufacturing prioritizes convenience and quick dissolvability. The former requires meticulous attention to detail in multiple stages, especially during roasting, which significantly impacts the final coffee flavor [5, 23]. In contrast, instant coffee production places emphasis on extracting, concentrating, and dehydrating coffee to create a soluble form, making it a convenient and accessible option for consumers seeking a quick caffeine fix. Understanding the disparities between these two processes highlights the versatility of coffee and caters to a wide range of consumer preferences.

Comparing the key stages in green coffee bean processing and instant coffee manufacturing reveals a mix of shared commonalities and notable differences. Both processes involve harvesting ripe coffee cherries, sorting, and cleaning to eliminate impurities, and maintaining quality through measures like sorting, grading, and sensory evaluation. However, crucial distinctions emerge. Green coffee beans undergo roasting to develop flavor and aroma, a step absent in instant coffee manufacturing. The latter entails extraction and concentration to obtain soluble compounds, not required in green coffee bean processing. Drying methods differ;

green beans are sun-dried or mechanically dried, while instant coffee employs specialized methods like freeze-drying or spray drying. Freshly brewed coffee made from roasted and ground beans has a distinct flavor and aroma that is often preferred by coffee connoisseurs [134].

Instant coffee, on the other hand, is often made from low-quality Robusta beans, which have an earthier flavor that goes well with milk and sugar [91, 135]. A cup of instant coffee contains between 60-80 mg of caffeine, whereas a freshly brewed coffee made with grounds has anywhere between 80-120 mg of caffeine [135]. The shelf life of instant coffee is longer compared to ground coffee, which is used for brewing [136]. Additionally, instant coffee is packaged in various consumer-friendly forms, while green coffee beans are primarily sold in bulk or smaller quantities for home roasting [77, 137]. Instant coffee produces no waste grounds, and there is also less packaging to product ratio, making it more environmentally friendly compared to fresh coffee [138, 139]. However, fresh coffee produces waste coffee grounds, which can be reused as fertilizer or turned into face scrubs [140]. In essence, these commonalities and differences define the unique characteristics of green coffee beans and instant coffee.

Life Cycle Analysis (LCA) of Coffee Manufacturing Life cycle analysis (LCA) is a systematic approach used to assess the environmental impacts associated with a product throughout its entire life cycle, from raw material extraction to end-of-life disposal. In the case of coffee manufacturing, LCA provides valuable insights into the environmental burdens and sustainability performance of the industry. The life cycle of coffee begins with the cultivation of coffee plants. The environmental impact at this stage includes land use for coffee plantations, water consumption for irrigation, and the use of agrochemicals such as fertilizers and pesticides.

LCA studies analyze the energy and resources required for coffee cultivation, as well as the potential impacts on soil quality, biodiversity, and local ecosystems. Giraldi-Díaz et al. [141] evaluated the environmental impact of coffee production in Colombia using LCA methodology. The study considered various stages of the coffee life cycle, including cultivation, processing, packaging, transportation, and consumption. The results revealed that the cultivation stage had the highest environmental impact due to factors such as land use change, pesticide use, and water consumption. The study emphasized the importance of sustainable agricultural practices to reduce these impacts. It was also reported that the cultivation of coffee requires an average of 1,400 L of water per kilogram of coffee produced [142].

This is a significant amount of water, especially in regions where water is already scarce. Additionally, it was found that coffee cultivation can lead to deforestation and habitat loss, as forests are cleared to make way for coffee plantations. Once the coffee beans are harvested, they must be transported to the manufacturing facility. This can also have a significant environmental impact, particularly in terms of greenhouse gas emissions. Up to 20% of the total carbon footprint of coffee production was reported for the transportation of coffee beans from the farm to the factory [143]. Furthermore, Anil Kumar, Saleem Khan and Balakrishnan [144] indicated that shade-grown coffee and wet processing had lower carbon footprints compared to sun-grown coffee and dry processing. The total energy, carbon emissions, water use, and wastes are assessed over the life cycle of a cup (100 ml) of coffee.

The energy use, water use, and carbon emissions are summarized in Table 2 for various stages of the coffee production process, including green coffee handling & cleaning, roasting, grinding, filling & packing, and conditioning [2]. Finally, the end-of-life disposal of coffee manufacturing

Table 2 Summary of energy and water use and carbon emission for one cup (100 mL) of coffee [2]

Process	Energy use MJ per 100 mL	Water use (liters/100 mL)	g of CO_2 Equivalent per 100 mL
Irrigation (4000 m^3/ha/yr)	0.24	25	6.08
Brewing	0.86	1.96	44.03
Washing	0.39	1.22	20.87
Cup and Coffee Equipment Manufacture	0.05	0.07	3.29
Distribution	0.03	0.05	2.79
Processing	0.05	-	2.63
Packaging	0.04	0.1	2.79
Delivery	0.04	-	2.63
Treatment	0.11	0.13	8.38
Cultivation	0.2	0.37	24.32
End of Life Wastes	-0.07	-0.07	-3.78
Total	1.94	28.83	114.03

waste can also have environmental impacts. Usually, coffee grounds and other waste products from coffee manufacturing can be composted and used as a nutrient-rich soil amendment [145]. However, if not disposed of properly, these waste products can end up in landfills and contribute to methane emissions.

Sustainability Practices in Coffee Production Sustainability practices in coffee production are aimed at reducing environmental harm, fostering social responsibility, and securing economic viability along the coffee supply chain. These encompass various facets, including the adoption of agroforestry systems, effective water management, and support for fair trade initiatives. Agroforestry systems, as exemplified by shade-grown coffee cultivation, have been shown to have positive effects on biodiversity preservation, carbon sequestration, and soil fertility improvement [146]. By incorporating trees into coffee farms, a more sustainable ecosystem is created, supporting wildlife habitats and reducing the need for synthetic inputs. In addition, regenerative agriculture is an integral part of sustainable coffee production, which focuses on repairing soils damaged by conventional farming methods and uses a variety of methods to increase soil fertility and health [147]. Also, effective water management, which involves adopting efficient irrigation methods and reducing water usage to combat the environmental implications of water scarcity [148]. Additionally, fair trade initiatives, supported by organizations such as Fairtrade International, play a vital role in coffee sustainability by ensuring equitable prices for farmers and endorsing social welfare through ethical sourcing practices and community development projects.

Assessment of the Environmental Impact Coffee, a globally beloved beverage, is central to many people's daily routines. However, the coffee manufacturing process wields significant environmental consequences that demand careful examination to ensure sustainability and identify avenues for improvement. Deforestation is a critical issue, especially in biodiverse regions like tropical rainforests, where expanding coffee plantations lead to habitat destruction and reduced carbon sequestration. Kelley, Pitcher and Bacon [149] found that shade-grown coffee, preserving forest cover, enhances biodiversity. Climate change and deforestation are major threats to coffee production, with 60% of wild coffee species at risk of extinction due to these factors [150]. Practices, such as shade-grown coffee, can help boost biodiversity, prevent soil erosion, and act as a carbon sink. Excessive water usage during coffee production strains local resources and can result in water scarcity, while improper wastewater disposal pollutes nearby water bodies [151]. Coffee manufacturing's energy consumption, reliant on diverse energy sources, can significantly impact greenhouse gas emissions [152, 153]). Nab and Maslin [154] demonstrated that renewable energy reduces the carbon footprint in coffee production. Furthermore, coffee manufacturing contributes to greenhouse gas emissions primarily through deforestation, energy use, transportation, and waste management. Branca et al. [155] emphasized the significance of sustainable land management practices and efficient input use to minimize emissions. Lastly, waste generation from coffee manufacturing poses a pollution risk, but Sumardiono et al. [156] suggested that coffee pulp can be effectively converted into biogas, reducing waste and emissions.

In conclusion, the assessment of coffee manufacturing's environmental impact is pivotal for the industry's sustainability, addressing factors like deforestation, water usage, energy consumption, greenhouse gas emissions, and waste management to guide efforts toward a more sustainable coffee production system.

Significance of Quality, Efficiency, and Sustainability In recent years, there has been a growing interest in sustainable and efficient coffee processing methods that prioritize quality and minimize waste. Quality is a critical aspect of coffee processing, as it directly affects the taste, aroma, and overall consumer experience. High-quality coffee demands meticulous attention to every stage of production, including harvesting, processing, and dehydration. Advanced drying methods like freeze-drying and vacuum-drying allow for precise control over the drying process, resulting in uniform moisture removal and preservation of the coffee's unique flavor compounds. The maintenance of these delicate aroma and taste profiles is central to satisfying the discerning palates of coffee consumers. Quality enhancement through controlled dehydration methods ensures that the final product meets the exacting standards of the specialty coffee market [26]. It was reported that the quality of coffee is influenced by factors such as bean variety, roast level, grind size, and brewing method [157]. Therefore, it is essential to ensure that the coffee beans are of high quality, and that the processing methods used do not compromise their flavor and aroma.

Efficiency is another important consideration in coffee processing, as it can significantly impact the cost and sustainability of the production process. A study found that efficient processing methods can reduce waste and energy consumption, leading to cost savings and a more sustainable production process [158]. Traditional sun-drying methods can be resource-intensive and time-consuming, potentially leading to energy wastage and prolonged processing times. In contrast, advanced dehydration techniques, such as vacuum-drying and spray-drying, optimize energy usage, reduce water consumption, and expedite the drying process. Additionally, efficient processing methods can help to increase the yield of usable beans, reducing the amount of waste and improving the overall efficiency of the production process.

Efficiency not only minimizes environmental impact but also results in cost savings for coffee producers. In a competitive market, operational efficiency is key to the economic viability of coffee cultivation and processing [155]. Sustainability is a critical aspect of coffee processing, as it can impact the environmental, social, and economic aspects of the production process. Ferrater-Gimena, Sayson and Sy [159] found that sustainable coffee processing methods can reduce the environmental impact of coffee production, including water and energy consumption, and can also improve the social and economic well-being of coffee farmers. Additionally, sustainable processing methods can help to ensure the long-term viability of the coffee industry, by reducing the negative impact of coffee production on the environment and society. Sustainable coffee cultivation, processing, and dehydration methods contribute to the preservation of ecosystems and promote responsible land management. Modern dehydration techniques, known for their reduced energy and resource consumption, align with sustainable agricultural principles, reducing the carbon footprint of coffee production. Sustainability is not only a moral imperative but also a selling point for environmentally conscious consumers, creating a market advantage for coffee producers [141].

Management of Byproducts in Coffee Manufacturing The coffee industry generates significant quantities of byproducts, including coffee pulp, husk, parchment, silver skin, and spent coffee grounds. Managing these byproducts is vital for environmental sustainability and exploring value-added applications. Various strategies can be employed for effective byproduct management. Pre-treatments, followed by recovery procedures, endow value-added products such as natural antioxidants, vitamins, enzymes, cellulose, starch, lipids, proteins, and pigments, which are of high significance to the pharmaceutical, cosmetic, and food industries. Additionally, the utilization and industrial application of coffee by-products are essential, especially considering the enormous amounts of coffee by-products generated by the coffee industry.

Coffee pulp can be composted for organic fertilizer, utilized for anaerobic digestion to produce biogas, or employed as animal feed. Coffee husk finds use as biomass fuel, animal bedding, or a soil amendment. Coffee parchment, one of the most underutilized coffee by-products, is produced during coffee processing. It has been identified as having significant potential for value addition. The parchment can be composted, used as a mushroom cultivation substrate, or pyrolyzed into biochar. Coffee silver skin can be utilized for extracting bioactive compounds, animal feed, or soil amendment. Spent coffee grounds can be composted, converted into biofuels, or employed in food and beverage applications. These by-products have been identified as valuable resources for the production of enzymes, aroma compounds, mushrooms, and other value-added products, thus promoting sustainable development and adding value to the coffee industry.

Furthermore, the application of sustainable practices in managing coffee by-products aligns with the principles of regenerative agriculture, which focuses on repairing soils damaged by conventional farming methods and increasing soil fertility and health. These management practices help minimize waste and contribute to a more sustainable coffee industry [144, 159, 160]. And they are integral to coffee manufacturing, promoting sustainability and reducing waste generation while opening up economic opportunities.

Knowledge Gap The entire subject of coffee powder either ground or soluble process is not sufficiently covered in the literature starting from the process to the physical properties. Chemical assessments and impact of caffeine on human health have been carried out more than the actual physical or thermal properties of the coffee [30, 161]. Recent work done by Clarke and others covered most of the important aspects by diverse chapters, but still, this is almost two decades old work [77]. The production and variety of coffee have changed since then. The food engineering concepts are not fully covered with thorough research such thermochemical, physicochemical, and apparent or visual properties. Hence, the dehydration process, evaporation, extraction or even adulterated of coffee lack of any recent updated information and it is essential to have updated and up-to-date information and studies. On the other hand, the coffee industry is doing well that it doesn't need to reveal any information, but more patents are filed rapidly. For example, Starbucks, Nestle, and General Foods are three biggest producers of fresh or instant coffee, but the information and data are not published, where their patents are countless on coffee derived products.

Conclusion

The advancements in coffee manufacturing, particularly in dehydration techniques, play a crucial role in enhancing the quality and sustainability of coffee production. Through a detailed examination of various dehydration methods such as spray-drying and freeze-drying, it is evident that these techniques not only extend the shelf life of coffee but also preserve its essential flavor and aroma compounds. The effective grading and sorting of green coffee beans further ensure that only the highest quality beans proceed through the production process, ultimately resulting in a superior final product.

Quality control measures, integrated throughout the manufacturing process, are vital for maintaining the integrity of coffee. Technological innovations in quality control, such as real-time monitoring and automated systems, have significantly improved the consistency and safety of coffee products. These advancements contribute to meeting the growing consumer demand for high-quality coffee while adhering to sustainability practices.

Future research should focus on optimizing existing dehydration techniques and exploring new methods that can further enhance the quality and efficiency of coffee production. Additionally, the integration of advanced technologies in quality control should be continually assessed to ensure the highest standards are met. By embracing these advancements, the coffee industry can achieve greater sustainability, efficiency, and product excellence.

In summary, the continuous evolution of coffee manufacturing techniques underscores the industry's commitment to quality and innovation. As consumer preferences evolve, so too must the methods employed in coffee production, ensuring that every cup of coffee meets the highest standards of excellence.

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Declarations

Competing Interests The authors declare no competing interests.

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