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Key issues and challenges in spice grinding

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ABSTRACT

Spices are ubiquitous in the daily diet and gained more attention as preservatives, flavor, aroma, and therapeutic agents in the food and pharmaceutical industry. The quality standards of spices are closely associated with processing techniques. In spice processing, grinding plays an important role and needs special emphasis considering the problems of significant quality loss due to heat generation. Grinding is a simple unit operation but interlinked with crop parameters, machine parameters, and pre-treatments. Several techniques and methods are being applied in the spice grinding process like conventional grinding (hammer, plate, pin mill), superfine grinding (ball, jet, roller mill), improved grinding (cryogenic, dry ice, pre-chilling, chilled air, water jacket, stage grindings). Convectional methods follow several challenges like more energy consumption, material stability, cost economics, etc. Among improved grinding methods, cryogenic grinding has proved a superior method for spice grinding. Although proven technology, it has till certain challenges in design, optimization in liquid nitrogen use, initial and operational costs. The major objective of this paper is to identify critical factors associated with the quality retention of spices during grinding and a comprehensive understanding of their cause-effect relationships. Attribute coding and the DEMATEL approach were applied for determining the cause-effect relationship of identified factors. The review highlights the challenges, opportunities, and perspectives of each grinding technique. The findings of the study intended to guide researchers, processors, and manufacturers in reducing quality loss during spice processing and also to serve as a ready reckoner for developing efficient and novel spice grinding technologies.

1. Introduction

India is the top spice producing, consuming, and exporting country in the world, accounting for 50% of the global trade (Board, 2019). Indian spices are known for their elegant aroma, flavor, and therapeutic value. About 80–85% of the total spices produced in the country are consumed at the domestic level (Singh and Solanki, 2015). The quality of any spice can be determined by its intrinsic and extrinsic traits. The unique characteristic of any spices is mainly because of a specific volatile oil or a compound that it contains. These compounds are embodied in the plant cell matrix and can be easily made available after grinding (Zachariah et al., 2012). For this reason, major spice crops such as red chili, coriander, turmeric, etc., are preferably consumed in powder form. The ground powder shows enormous export and local market potential. Hence, grinding becomes a critical unit operation in spice processing.

Grinding is an age-old technique of particle size reduction to produce powders that can be used as intermediate or end products. Grinding aims to reduce the size of the particle by mechanical means such as impact, compression, shear, and cutting (Sahay and Singh, 1996). Hammer mill, plate mill, ball mill, pin mill, roller mill are commonly used grinding equipment for spice (Balasubramanian et al., 2016). The schematic diagram, principle, and application of different size reduction equipment are presented in Table 1. Grinding is an energy-intensive process in which only 1% of the total input energy is utilized to reduce particle size and rest of the energy is dissipated as heat (Jung et al., 2018). Consequently, the grinding process is accompanied by a substantial rise in the temperature of the ground product, ambient air, and grinding mill (Balasubramanian et al., 2012). As the aromatic, flavoring and therapeutic components present in spices are heat liable in nature, an increase in temperature during grinding significantly lowers the quality of ground spices (Liu et al., 2013). Product temperatures of up to 90 °C in ambient grinding (Bera et al., 2001), 40 °C in wet grinding (Jung et al., 2018), and 26 °C in freeze grinding (Mathew and Sreenarayanan, 2007) were observed. Temperature-induced quality loss to the tune of 40% was reported in the conventional grinding process (Bera et al., 2001). Besides quality loss, temperature also results in clogging, higher oxidation of the

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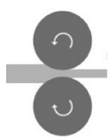
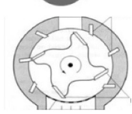
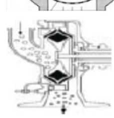
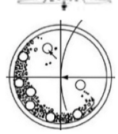
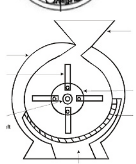
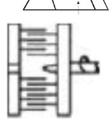
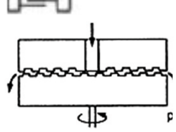
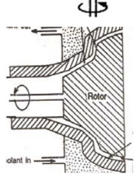
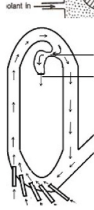
product, higher energy consumption, and also induces tensile residual stress, reducing tool life (Meghwal and Goswami, 2014). Therefore, minimizing heat generation and quick removal of heat during grinding becomes crucial to maintaining the end product's quality.

The type of mill influences the rate and amount of heat generated during grinding, the principle of grinding, the degree of grinding (Meghwal and Goswami, 2014), and the properties of the material (Jung et al., 2018). Several techniques and technologies have been developed to remove heat generated during grinding. Circulation of cold water (Bandara et al., 2015b) or low-temperature air around the grinding chamber (Shelake and Dabhi, 2019) lowers heat generated to some extent. Mixing dry ice and prechilling material significantly decreased grinding zone temperature and improved final product quality (Mathew and Sreenarayanan, 2007). However, these techniques are inefficient in removing the quantum of heat generated during grinding. Cryogenic grinding (Fig. 1), a method in which liquid nitrogen (boiling point of −195.6 °C) is being used to pre-freeze the material before grinding (Balasubramanian et al., 2012) and removing heat during grinding, is the advanced and effective method to maintain the quality of spices during grinding (Saxena et al., 2015). Besides low-temperature grinding, cryogenic grinding has several advantages: reducing grinding force, lower specific energy requirement, no sieve clogging, etc. (Singh and Goswami, 1999). Very high initial investment and operational cost, scarce in the availability of liquid nitrogen and high ratio of liquid nitrogen to material hindering the adaptability of this technology (Wilczek et al., 2004).

Retaining heat-sensitive ingredients of the food during sustainable and cleaner grinding process is a dynamic challenge for a food processor. The heat generation during grinding is influenced by several products and process parameters and principles. Temperature plays an important technological problem, particularly with heat-sensitive products, high-fat content, and thermoplastic substances (Gao et al., 2020). This article represents a comprehensive view of spice grinding techniques, focusing on critical quality control pregrinding and grinding process parameters to identify the most influential parameters and understand their cause-effect relationship. This work also intends to guide food

Table 1
Size reduction equipment.

Type	Schematic	Principle	Application
Roller mill		Compression and shear	Sugar cane, chocolate, rye, oats, wheat, oilseed
Knife mill		Cutting	Tea leaves, rubber bales, cheese, leaf, bark, and root of drugs
Turbo Mill		Impact, shearing, and Cutting	cacao beans, fat, flax meal, milk powder, salt
Ball mill		Impact and Shear	Coal, pigment, felspar
Hammer mill		Impact	Fibrous solid, Sugar, tapioca, dry vegetables, Spices, food grains, hard rock
Pin mill		Impact	Sugar, caffeine, fiber, flake, yeast, wax, milk powder, spices
Plate/Burr mill		Crushing and shear	Wheat, coffee beans, salt peppercorns, spices, poppy seeds
Colloid mill		Shear	Toothpaste, Cream, Fruit jam, honey, butter, corn and soybean milk, Dyestuff, Fish oil
Fluid energy mill (Ultrafine)		Impact and attrition	Moderately hard and friable material

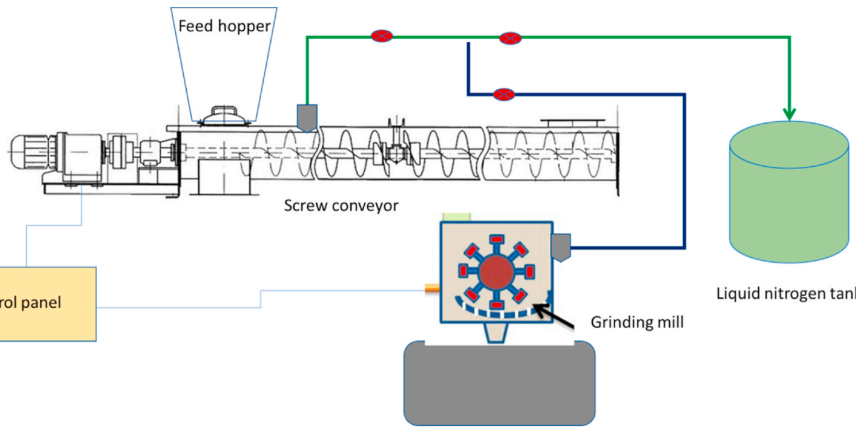


Fig. 1. Cryogenic grinding.

processors and engineers in understanding the cause-effect relationship of one process parameter over another to select, design, and develop spice grinding technology for energy-efficient and quality grinding.

2. Literature review

This segment consists of paper highlights in the area of spice grinding. Existing literature on spice grinding was thoroughly reviewed and categorized (Fig. 2) to identify critical factors influencing the quality of the final product. Further, identified factors and quality/performance indices were grouped and presented as cause-effect relationships (Fig. 3).

2.1. Crop parameters

Crop parameter includes attributes like variety, moisture content, hardness, and other engineering properties. Growing conditions have been reported to significantly impact thousand kernel weight, ash content, and physical and chemical properties of grains (Singh et al., 2012). Crop moisture content is a key factor defining the particle size

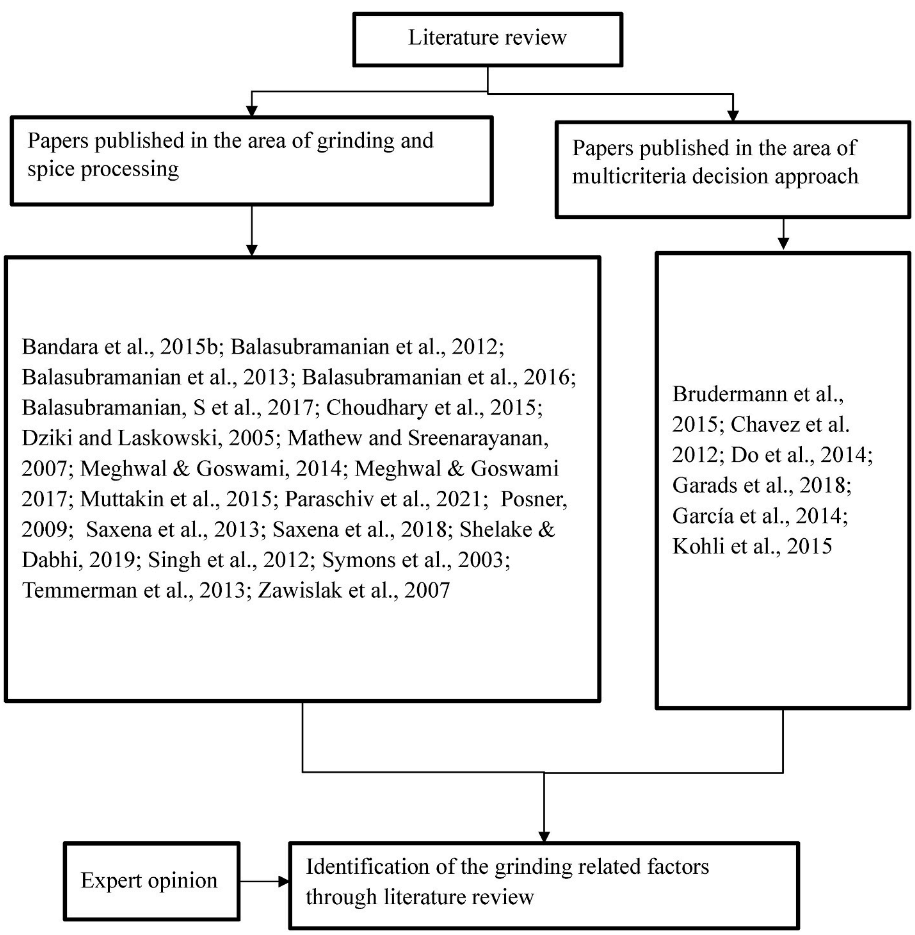


Fig. 2. Literature review hierarchy.

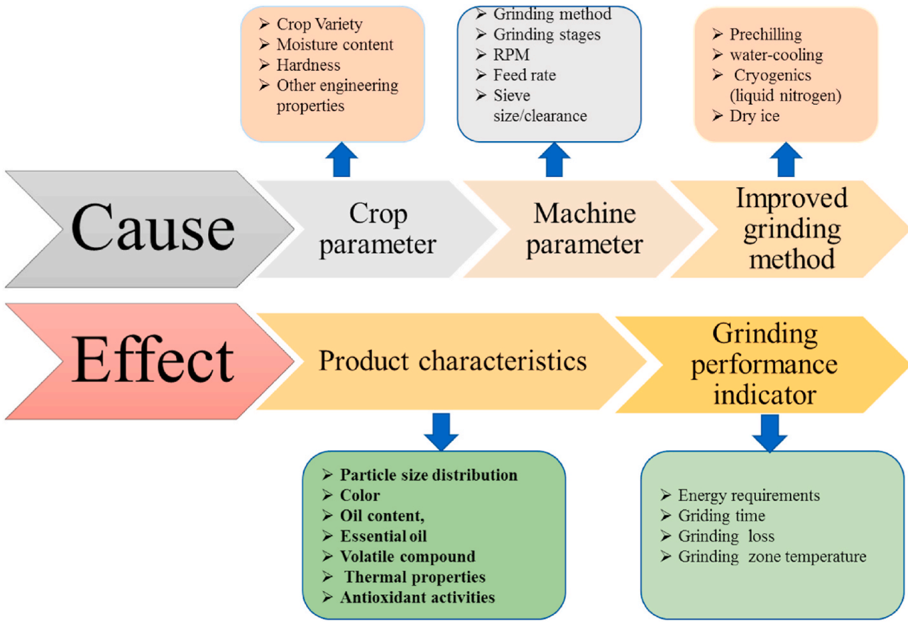


Fig. 3. Cause and effect attributes of spice grinding process.

distribution of ground product (Saxena, 2013) and grinding energy (Meghwal and Goswami, 2017). Further, there is a linear relationship between moisture and the mechanical properties of biological materials (Balasubramanian et al., 2017). Several studies have pointed out the relations between kernel hardness and the size reduction process. In general, brittleness reduces with increased moisture content, consequently increasing the energy required for grinding. Brittleness and tempering conditions affects the particle size, starch damage, milling yield, and functional properties of the powder (Dziki and Laskowski, 2005). Besides hardness, kernel weight, size, shape, and virtuousness affect the grinding process (Symons et al., 2003). Among these, shape and size are essential that define operational conditions and machines for grinding (Posner, 2000).

2.2. Machine parameters

Machine parameters include rotor/grinding tool speed, feed rate, grinding time, grinding zone temperature, and energy requirements. Selection of the grinding mechanism is the first and most crucial step, as it greatly impacts particle size distribution. Various grinding machines like a hammer, ultrafine, plate, roller, pin, ball mill and hand-pounding methods are being used for different spices (Balasubramanian et al., 2012). The efficiency of the grinding process is influenced by the design, operational and functional parameters of the mill. These parameters include the rollers' arrangement (Zawislak et al., 2007), speed, rotor type and number, distance between the rollers/plates, flutes profile, diameter of the plate, size of opening or clearance between grinding components, etc. (Meghwal and Goswami, 2014). Specific energy consumption and powder characteristics are affected by the grinding method or principle employed. For instance, a hammer mill is more energy-efficient than a knife mill and produces finer particles (Paraschiv et al., 2021). Comminution laws describe the relationship between the specific energy consumption and distribution of particle size. Different strategies were used when targeting small aperture sizes with the help of intermediate screens (Temmerman et al., 2013). These parameters were affected either individually or in combination and correlated in terms of rittinger's constant, kick's constant, bond's index, total surface area, average particle size, grinding effectiveness, and yield (Balasubramanian et al., 2013).

2.3. Improved grinding methods

To protect heat-sensitive and volatile components, grinding should be performed under reduced temperature. For this, mills equipped with a cooling system or cryogenic milling are required (Saxena et al., 2018). Improved grinding methods were developed to minimize or extract the heat generated during grinding process. Air (Shelake and Dabhi, 2019), water (Bandara et al., 2015b), liquid nitrogen (Balasubramanian et al., 2016), dry ice (Mathew and Sreenarayanan, 2007), dual-stage grinding (Choudhary et al., 2015), superfine jet milling (Muttakin et al., 2015) were used to retain the quality of the spices and herbs.

2.4. Multicriteria decision approach

Multicriteria decision approach tools such as DEMATEL, attribute coding, fuzzy analytic hierarchy process, analytical hierarchy process (AHP), SWOT, etc., are being successfully used in agriculture and allied science research. For instance, analytic hierarchy process for banana warehouse site location (García et al., 2014), SWOT analysis for prospects of biogas plant (Brudermann et al., 2015), and fuzzy analytic hierarchy process for the thermal process (Do et al., 2014). Kohli et al. (2015) studied the factors involved in cotton harvesting mechanization in India using the attribute coding approach. Chavez et al. (2012) define important criteria involved in post-harvest activities.

3. Research methodology

The present study used two approaches: attribute coding (Kohli et al., 2015) and DEMATEL (Gardas et al., 2018). The conceptual framework for developing an attribute-based model is presented in Fig. 4.

3.1. Attribute identification

Attribute is a specification that defines the property of an object or element. Attribute Coding provides essential data information for future use (Onwuegbuzie et al., 2016). For this purpose, the cause and effect analysis diagram (Fig. 3) is drawn to identify all the different attributes and other parameters of the spices grinding process that require attention from researchers, engineers, industrialists, and manufacturers in the subject area. The attributes identified under four categories: crop

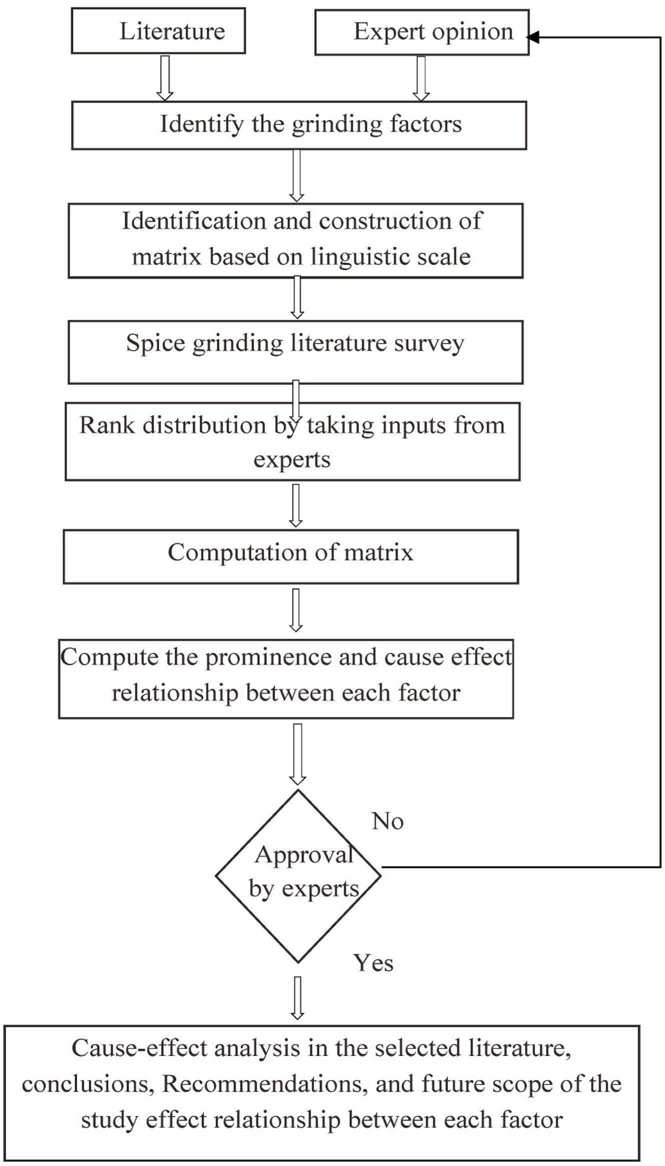


Fig. 4. A conceptual framework for developing an attribute-based model.

parameters, machine parameters, improved methods on product characteristics, and grinding performance indicator are shown in Fig. 3.

Step 1. Matrix Identification

The importance of attributes and relevance in the research publication are expressed in matrix form and given in Tables 2 and 3. For each publication, grading was done based on the importance of a specific attribute considered in that study.

Step 2. Identification and construction of matrix based on a linguistic scale

The attribute ratings were given on 5 points numeric scale, with 5 for the most important and 1 for the least important attribute.

3.1.1. Rank distribution

Rank distribution is given as per attribute importance and narrated thoroughly; the highest-grade points were decided by the degree of closeness described in the research publication. Based on the degree of closeness, grade points were allocated to that attribute. To find the importance of each attribute, the attributes are required to be evaluated and coded for a range of values. It is desirable to assess the attributes on

Table 2
Matrix for various attributes of the crop, machine, and improved grinding methods.

Attribute-based coding of the crop, machine, and improved grinding methods							
Attribute (Category A)	Research publication						
	P1	**P2**	**P3**	**P4**	… … … … … … … … … …. .	**Pn**	**∑A**
A1	a11	a12	a13	a14	… … … … … … … … … …. .	a1n	∑A1
A2	a21	a22	a23	a24	… … … … … … … … … …. .	a2n	∑A2
A3	a31	a32	a33	a34	… … … … … … … … … …. .	a3n	∑A3
. .	. .	. .	. .	. .	… … … … … … … … … …. …. … … … … … … … … …. .	. .	. .
(Category B) B7	b71	b72	b73	b74	… … … … … … … … … …. .	b7n	∑B7
. . .	. . .	. . .	. . .	. . .	… … … … … … … … … …. . … … … … … … … … … …. . … … … … … … … … … …. .	. . .	. . .
(Category C) Cm	cm1	cm2	cm3	cm4	… … … … … … … … … …. .	can	∑Cm
∑P	**∑P1**	**∑P2**	**∑P3**	**∑P4**	… … … … … … … … … …. .	**∑P7**	**∑P = ∑A**

Table 3
Matrix for effects of A, B, and C attributes on powder characteristics and grinding performance indicator.

Attribute-based coding of powder characteristics and grinding performance indicator							
(Category D)	Research publication						
	P1	**P2**	**P3**	**P4**	… … … … … … … … … …. .	**Pn**	**∑D**
D1	d11	d12	d13	d14	… … … … … … … … … …. .	d1n	∑d1
D2	d21	d22	d23	d24	… … … … … … … … … …. .	d2n	∑d2
. . .	. . .	. . .	. . .	. . .	… … … … … … … … … …. . … … … … … … … … … …. . … … … … … … … … … …. .	. . .	. . .
Dm	dm1	dm2	dm3	dm4	… … … … … … … … … …. .	dmn	∑d7
∑P	**∑P1**	**∑P2**	**∑P3**	**∑P4**	… … … … … … … … … …. .	**∑P26**	**∑P = ∑D**

one interval scale of 1–5 for uniformity. Table 4 indicates the proposed coding scheme individually and in combination with research publications. The attribute assigned with 5-grade points was ranked excellent given through discussion in the research paper with the help of a graph showing the relation between variable quantities, table, and text narrative. Attribute awarded with 4 points was considered under the outstanding category. Attributes with 4-grade points represented the table information with the help of text, data observation, and simultaneous effect on other parameters. Three grade points were expressed as good rank and presenting text with data form showing little information, but its effect was not discussed in the study. Two grade points considered under average level were discussed and examined in the text form without physical data. Attributes carried 1-grade point with poor rank (Kohli et al., 2015).

Step 3. Calculation of total influence and inner dependency matrix (DEMATEL approach)

X (initial direct influence matrix) = S.D

Where, $S = \min \{1/\max i \sum_{j=1}^{n} |d_{ij}|, 1/\max j \sum_{i=1}^{n} |d_{ij}|\}$

$$T \text{ (total influence matrix)} = X_1 + X_2 + \ldots + X_n = X(1-X)^{-1}, \text{ when } \lim \lim_{n\to\infty} (X)^n = [0]_{nXn}$$

$$D = (D_1, \ldots D_i, \ldots D_n) = (Di)nx1 = \left[\sum_{j=1}^{n} t_{ij}\right] nX1$$

$$R = (R_1, \ldots R_j, \ldots Rn) = (R_j)1xn = \left[\sum_{i=1}^{n} t_{ij}\right] 1xn$$

Di and Rj represent the sum of i^{th} row and j^{th} column of matrix T. 'D–R' represents the centrality factors and their influence between elements, and positive values mean that a criterion is a causal factor and a negative value implies a criterion is the effect factor. 'D + R' represents the causality factor and their degree of relationship. Higher values of 'D + R' mean stronger the influence of the parameter under consideration.

Step 4. Summation of grading points (Attribute based coding approach)

The summation of grading points gives the idea of each attribute in individual publications for the comprehensive view of spice grinding.

4. Results

The values of 'D–R' and 'D + R' along with the inner dependency of the matrix, are presented in Table 5. In the inner dependency matrix, the threshold (α) value of 0.4 was considered, obtained by averaging the total relation matrix. The values lower than 0.40 were omitted from the tables. This indicates that the high significance factors were depicted in Table 5. Based on the calculated values of 'D + R', grinding methods have the maximum value (15.74) followed by cryogenic grinding (15.04) and moisture content (11.42). These values reflect that the grinding method, along with cryogenic pretreatment influences the final product quality. The relative weights of attributes and their rank are presented in Table 6. Selected parameters were categorized as cause and effect along with their ranks. The matrix calculation to identify factors and cause-effect relationships by using the DEMATEL approach and attribute coding approach presents similar results.

In the Attribute coding approach, the summation of coding as per their importance in the research paper was calculated and presented in Table 7. It is observed from the table that the majority of researchers had discussed grinding methods. Machine and its related parameter are considered important with highest score (95) as the performance of grinding operation predominantly depends on the grinding mechanism (impact, attrition, shear, or compression). In improved grinding, water-cooling, pre-cooling of product/machine andr using cryogenics such as liquid nitrogen or dry ice (cryo-milling) were used to retain the quality of the spices. Among these attributes, cryogenic has the highest score (80) points and is discussed in depth. Most of the researcher had addressed the effect of cryogrinding on product quality as against ambient grinding. Cryogenic grinding provides higher retention of volatile oils per unit mass of spices maintaining the flavor. It leads to finer grinding with uniform particle distribution and without heat generation, which is suitable for spices and provides an inert atmosphere eliminating the oxidation process.

Moisture content was discussed most and given higher significance by most studies. The higher-grade points (45) for this attribute reflect its impact on spice grinding. It was observed that moisture substatinally influencing the grinding process, machine performance, and powder characteristics. As far as the performance of milling is concerned, various parameters like rpm, feed rate, sieve size, and grinding time were discussed in different studies. Among these attributes are feed rate, sieve size, and rpm/speed, with 39, 31, and 27-grade points. Only one researcher has shown the effect of grinding stages on product quality. These attributes strongly impact energy consumption, grinding losses, grinding capacity, and temperature of the grinding zone. Though the influence of crop variety (18) has been studied by limited researchers, the importance of this parameter is not analyzed in detail concerning flour characteristics and machine performance. However, crop variety/genotypes are the foremost consideration in volatile oil's yield, quantity, and quality.

Engineering properties with 17-grade points are considered essential for food processing methods and equipment design, which depends on moisture content. It is used to assess other properties and also used for product quality determination. Other parameters like hardness and kernel mass are concerned; none of the authors have given importance to these attributes and not considered these parameters in their studies.

4.1. Publication-wise attribute coding

The coding matrix of all publications is presented in Table 7. Two publications (P7 and P24) received grade points higher than 20, 4 publications (P9, P18, P25, and P26) received less than ten, and the rest of the publications were between 10 and 20 grade points. Publication P7 (Meghwal and Goswami, 2013) received higher grade points, i.e., 26 followed by P24 (Singh and Goswami, 2000) with 22-grade points, emphasizing improved method, feed rate, speed and sieve size. Grinding

Table 4
Rank distribution of attribute coding.

S.N	Attribute coding	Rank
1.	5	Excellent
2.	4	Very good
3.	3	Good
4.	2	Average
5.	1	Poor

Table 5
Inner dependency and influence matrix.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D + R	D-R
A1		0.56	0.56	0.63	0.65				0.65				0.57	9.4	−3.37
A2	0.40	0.53	0.53	0.50					0.68	0.66			0.63	11.42	−3.06
A3									0.72	0.7			0.66	9.26	−2.87
B1	0.75			0.66	0.7	0.47			0.7	0.68			0.64	15.74	−2.87
B2	0.72	0.68	0.51	0.69	0.69	0.57				0.67			0.63	7.69	−2.75
B3	0.69			0.68	0.68					0.66			0.62	8.13	−1.85
B4	0.68			0.63	0.51				0.51	0.5			0.47	10.25	−1.08
B5	0.45				0.63				0.63	0.61			0.57	11.11	−0.87
C1		0.55	0.5	0.63	0.69	0.69	0.5		0.69	0.68			0.65	7.68	−0.75
C2		0.75	0.69	0.65	0.62	0.62	0.65		0.62	0.61			0.69	15.04	−0.58
C3		0.62	0.63	0.69	0.61	0.61	0.6		0.61	0.6			0.67	7.14	−0.25
C4		0.61	0.57	0.67	0.55	0.55	0.56		0.55	0.62			0.66	8.65	−0.21
D-R	−3.37	−0.87	−3.06	−2.87	−2.75	−0.75	−0.58	−0.2	−1.08	−1.85	−0.21	−0.25	−2.87		−0.2

Table 6
Relative weights of selected parameters.

Cause-Effect group criteria	D-R	Rank		Cause-Effect group criteria	D-R	Rank		
Crop variety (A1)	3.24		Cause	Particle size distribution	−3.37	1	Effect	
Moisture content (A2)	6.12	3	Cause	Color	−0.87	3	Effect	
Engineering properties (A3)	4.02		Cause	Volatile oil content	−3.06	2	Effect	
Grinding types (B1)	7.37	1	Cause	Volatile compounds	−2.87	5	Effect	
Grinding stages (B2)	2.89		Cause	Moisture content	−2.75		Effect	
RPM/speed (B3)	1.18	6	Cause	Engineering properties	−0.75		Effect	
Sieve size/Clearance (B4)	4.23	5	Cause	Antioxidant properties	−0.58		Effect	
Feed rate (B5)	5.47	4	Cause	Proximate composition	−0.2		Effect	
water (C1)	2.29		Cause	Thermal properties	−1.08		Effect	
Cryogenic (C2)	7.06	2	Cause	Energy requirement	−1.85	6	Effect	
Dry ice (C3)	3.89		Cause	Grinding time	−0.21		Effect	
Chilling (C4)	3.47		Cause	Grinding loss	−0.25		Effect	
				Grinding zone Temperature	−2.88	4	Effect	4

time, rotor speed, and energy requirement was high in ambient grinding and low specific surface area compared to cryogenic grinding. These parameters were directly related to moisture content, but feed rate was inversely correlated with moisture for both regular and cryogenic grinding (Meghwal and Goswami, 2013). Singh and Goswami (2000) reported that the feed rate, speed, sieve size, and grinding temperature significantly affected the volatile oil content, particle size, and specific energy consumption for clove grinding. P1 received the third rank with 19 points and the study includes the different sieve sizes, ambient and low (refrigerated sample) and ultra-low (dry ice) temperature conditions on product quality, grinding zone temperature, energy consumption, and particle size distribution. Ultra-low temperature (−3.33 to −1.25 °C) has a significant effect on the retention of volatile oil and oleoresin content with a 2–3% increase in moisture content of the powder.

Publications P5 (Saxena et al., 2014a; 2015), P19 (Choudhary et al., 2015), P20 (Balasubramanian et al., 2013), and P23 (Barnwal, P et al., 2014b) received 18 points. Saxena et al. (2014, 2015) studied the effect of grinding methods in retaining different properties regarding coriander genotype. Choudhary et al. (2015) emphasized grinding stages (single- and double-stage grinding). They reported that double-stage grinding contained more volatile oil, active compounds of oleoresin and curcumin, and fine turmeric powder than single-stage. P20 Balasubramanian et al. (2013) evaluated the effect of moisture content, screen aperture size, and feed rate at constant rotor speed on specific energy consumption and particle size distribution. Barnwal et al. (2014b) studied the effect of moisture content, turmeric grades, and improved grinding method (cryo vs. ambient) on physicomechanical characteristics of turmeric rhizome. P13 (reference) with 17 points discussed the impact of product moisture content and cryogenic grinding on thermochemical and antioxidant properties of turmeric powder. Cryogrinding retained 80–95% of chemical properties regardless of sample moisture. P3 (Mallappa et al., 2015), P6 (Manohar and Sridhar, 2001), P8 (Barnwal, P et al., 2015), P12 (Goswami and Singh, 2003.) and P17 (Meghwal and Goswami, 2014) received 16 points. P3 discussed the milling methods in combination with temperature on the quality of chili powder. Capsaicin content and nutrient retention are more in cryogrinding followed by low-temperature pulverizer and simple pulverizer. Similarly, P6 discussed the comparison of ambient and cryo grinding on the size and shape of particles. P8 emphasized sample moisture content and grinding method (hammer and pin mills) on quality parameters of coriander powder. Compared to pin mill, hammer mill yields more fine coriander. There was no significant difference in essential oil content observed in both mills with different moisture content. A significant difference in total flavonoid content and DPPH content was observed in the grinding method and total phenolic content was reduced with moisture content regardless of the grinding process.

P12 publication studied the feed rate and improved grinding method on energy consumption and bonds index. An optimized feed rate of 24 kg/h resulted in lower specific energy consumption and minimum work index with appropriate particle size distribution and size reduction ratio. The low feed temperature also had an important role in reducing the energy consumption per kilogram of material fed into the grinder. Meghwal and Goswami (2014) reported that rotor, pin, and hammer mills were suitable for grinding at a feed rate of 1.35 kg/h under ambient conditions and 1.47 kg/h under cryogenic grinding. Ball mill could be used for a feed rate of 0.0936 kg/h and 0.1248 kg/h under ambient and cryogenic grinding. Time is taken for a fixed amount of sample in order of ball mill followed by rotor mill, pin mill, and hammer mill. Similarly, for feed rate, decrease in hammer mill followed by rotor mill, pin mill, and ball mill. Rotor mill was found to be the most suitable among all grinders for fenugreek and black pepper grinding. P16 with 15 points studied the effect of cryogenic and ambient grinding on coriander, fenugreek, and black pepper. P10, P14, and P21 received 13-grade points. Studied the effect of cryogenic grinding for king chili (P14)

Table 7
Paper wise coding for different attributes of crop, machines & its performance and treatment.

Attribute (Category A)	Attributes	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20	P 21	P 22	P 23	P 24	P 25	P 26	∑A
Crop Parameter																												
A1	Crop variety	0	0	1	0	4	0	1	1	0	1	3	0	0	0	0	1	0	0	0	0	3	0	2	0	0	1	18
A2	Moisture content	2	2	0	0	0	0	5	5	2	0	1	1	5	1	0	2	2	0	5	5	1	0	5	1	0	0	45
A3	Engineering properties	0	0	3	0	0	2	0	3	0	0	0	0	0	2	0	2	0	0	4	1	0	0	0	0	0	0	17
	$\sum P_x$	2	2	4	0	4	2	6	9	2	1	4	1	5	3	0	5	2	0	9	6	4	0	7	1	0	1	80
Machine parameter																												
B1	Grinding type	2	2	5	3	4	4	4	5	5	5	2	3	3	5	5	4	5	3	3	1	2	5	4	3	5	3	95
B2	Grinding stages	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5
B3	RPM, speed	0	2	1	0	2	2	2	2	0	0	0	2	2	0	0	1	0	1	1	1	1	0	1	5	1	0	27
B4	Sieve size/ Clearance	4	2	0	2	1	2	5	0	1	2	0	0	0	0	0	0	0	0	0	5	0	2	0	5	0	0	31
B5	Feed rate	3	1	1	1	2	1	4	0	1	0	0	5	2	0	0	0	4	1	0	5	1	1	1	5	0	0	39
	$\sum P_y$	9	7	7	6	9	9	15	7	7	7	2	10	7	5	5	5	9	5	9	12	4	8	6	18	6	3	197
Improved grinding method																												
C1	Water	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	6
C2	Cryogenic	0	0	5	5	5	5	5	0	0	5	5	5	5	5	5	5	5	0	0	0	5		5	5	0	0	80
C3	Dry ice	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
C4	Chilling	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	7
	$\sum P_z$	8	2	5	5	5	5	5	0	0	5	5	5	5	5	5	5	5	4	0	0	5	4	5	5	0	0	98
$\sum P = \sum P_x + \sum P_y + \sum P_z$		**19**	**11**	**16**	**11**	**18**	**16**	**26**	**16**	**9**	**13**	**11**	**16**	**17**	**13**	**10**	**15**	**16**	**9**	**18**	**18**	**13**	**12**	**18**	**24**	**6**	**4**	**375**

In Table 7, notations P1, P2, P3, …., P26 represent the research publications and can be mentioned as

P1	–	Mathew and Sreenarayanan (2007)	P14	–	Singh et al. (2018)
P2	–	Bandara et al. (2015a)	P15	–	Liu et al. (2018)
P3	–	Mallappa et al. (2015)	P16	–	Barnwal et al. (2014a)
P4	–	Pesek et al. (1985)	P17	–	Meghwal and Goswami (2014)
P5	–	Saxena al. (2014; 2015)	P18	–	Shanmugasundaram et al. (2018)
P6	–	Manohar and Sridhar (2001)	P19	–	Choudhary et al. (2015)
P7	–	Meghwal and Goswami (2013)	P20	–	Balasubramanian et al. (2013)
P8	–	Barnwal et al. (2015)	P21	–	Balasubramanian et al. (2016)
P9	–	Bandara et al. (2015b)	P22	–	McKee et al. (1993)
P10	–	Liu et al. (2013)	P23	–	Barnwal et al. (2014b)
P11	–	Sharma et al. (2014)	P24	–	Singh and Goswami (2000)
P12	–	Goswami and Singh (2003).	P25	–	Murthy et al. (1996)
P13	–	Barnwal et al. (2016)	P26	–	Kuang et al. (2011)

Table 8
Paper wise coding of powder characteristics.

Attribute (Category A)	Attributes	Research publication																									
Attribute-based coding of powder characteristics and grinding performance indicator																											
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	∑D
D1	particle size distribution	5	0	0	0	0	5	5	4	5	1	1	4	0	5	0	5	5	5	5	5	0	5	0	5	4	5	79
D2	color	0	4	5	0	0	0	0	5	5	5	0	0	5	5	0	5	5	5	5	0	0	5	5	1	0	0	65
D3	Volatile oil content	5	4	2	5	5	0	2	4	0	5	5	0	5	0	5	0	2	5	5	0	0	4	0	5	5	0	73
D4	volatile compounds	5	4	4	5	5	0	0	1	0	5	5	0	5	0	5	0	0	2	4	0	0	4	0	1	5	0	60
D5	Moisture content	3	3	3	0	0	0		0	3	0	0	0	0	0	3	0	0	0	0	0	0	4	0	0	0	0	19
D6	Engineering properties	0	0	0	0	0	0	4	0	0	0	0	0	0	5	0	0	0	0	0	3	3	0	5	0	0	0	20
D7	antioxidant properties	0	0	0	0	5	0	0	5	0	0	5	0	5	0	5	0	0	0	0	0	0	4	0	0	0	0	29
D8	proximate composition	0	0	5	0	0	0	0	0	4	0	0	0	0	4	5	0	0	0	0	0	0	0	0	0	0	0	18
D9	Thermal properties	0	0	0	0	0	0	0	5	0	0	0	0	5	0	5	0	0	0	0	0	5	0	5	0	0	0	25
D10	Energy requirement	3	0	2	0	0	0	5	1	4	0	0	5	0	0	0	4	5	5	0	5	0	0	0	5	4	0	48
D11	Grinding time	2	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	2	3	0	2	0	0	0	0	0	5	17
D12	Grinding loss	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	5	0	0	0	0	0	0	8
D13	Grinding zone Temperature	5	4	2	4	0	0	2	2	3	2	2	5	1	2	2	3	5	5	4	3	0	0	2	5	1	0	64
∑Pd		28	19	24	14	15	5	21	27	24	18	18	14	26	21	30	17	26	30	23	23	8	26	17	22	19	10	591

and pepper (P10) on the other hand P21 coriander crop genotypes. P22 received 12-grade points and discussed the effect of ambient, chilled, and liquid nitrogen grinding on nutmeg properties. P2, P4, and P11 received 11-grade points. Bandara et al. (2015a) discussed the mill types, i.e., four types of pin mills and three types' plate mills according to the capacity. Combination of operation in pin mill and plate mill, single pass without the screen and two passes, produce superior quality chili powder. Pesek et al. (1985) showed the effect of cryogrinding over ambient grinding for nutmeg, cinnamon, cumin, white pepper, and oregano. Other publications, P9, P15, P18, P25, and P26 received grade points less than 10. Among the above, P26 received only 4-grade points with simple fine grinding. In improved grinding methods, Mathew and Sreenarayanan (2007) have emphasized the dry ice treatment. Bandara et al. (2015b) discussed evaporative water-cooling treatment and Shanmugasundaram et al. (2018) examined pre-cooling using a deep freezer.

4.2. *Category-wise and publication-wise attribute coding*

Among 13 dependent attributes, particle size distribution is the most discussed parameter presented in Table 8. Particle size distribution obtained maximum grade points (79) followed by volatile oil content (73). Color of powder is an essential quality for consumer acceptance which received 65-grade points. Grinding zone temperature was considered necessary with grade point 64 followed by volatile compound (60). Energy requirement received 48-grade points. Some publications considered powder's antioxidant properties and thermal properties important and received 29 and 25-grade points. Some researcher includes grinding time, grinding loss but the impact is not observed in their studies. Moisture content, engineering properties, and proximate powder composition were less concerned, but 4–5 studies discussed the importance of these attributes getting grade points less than 20.

P15 (Liu et al., 2018) and P18 received the same grade points i.e., 30, which emphasizes particle size distribution, color, oil content, volatile compound, volume and surface area, thermal properties, proximate composition, and antioxidant activities. Liu et al. (2018) reported that essential oil, piperine, unsaturated fatty acids, and monoterpenes content were reduced. In contrast, insignificant changes were found in starch, lipid, amino acid, protein, and thermal properties after six months of storage at 4 °C despite the grinding technique. P1 (Mathew and Sreenarayanan, 2007) received 28-grade points and discussed specific energy, grinding time, and zone temperature. P8 (Barnwal et al., 2015) received 27-grade points and examined the particle size distribution, color, volume and surface area, thermal properties, and antioxidant activities. Particle size, surface, and volume mean diameter increased significantly with moisture content (6.4–13.6% Dry basis). Color and antioxidant values varied with the grinding method. Thermal conductivity linearly varied with temperature and moisture. Coriander powder ground using hammer mill had lower specific heat and higher thermal conductivity than that of pin mill.

P13, P17, and P22 received the same grade points, i.e., 26. Barnwal et al. (2016) discussed the chemical, thermal and antioxidant properties of turmeric powder. Meghwal and Goswami (2014), discussed the grinding method in ambient and cryogenic conditions on different properties of fenugreek and pepper. The specific surface area was observed high in rotor mill followed by hammer mill, pin mill, and ball mill. Power consumption is high in pin mill followed by hammer mill, rotor mill, and ball mill. Temperature rise in ambient and cryogrinding is high in pin followed by hammer, rotor, and ball mill. On the other hand, McKee et al. (1993) emphasized volatile oil, percentage of oleoresin, particle size distribution, moisture content, and antioxidant capacity of nutmeg ground under ambient, chilled, and liquid nitrogen. The temperature had no significant effect on particle size, uniformity, and moisture content. Volatile oil and oleoresin were significantly different from ambient to chilled and nitrogen but not significant from chilled to nitrogen. Overall, color and oleoresin across batch-wise were more consistent and better results were obtained in the nitrogen grinding method.

P3 and P9 received 24-grade points. P3 discussed the cryogenic effect on color, proximate composition, and capsaicin content of byadagi chilli. In a cryogenic pulverizer, the retention of nutrients, color, and capsaicin content was more than a low-temperature pulverizer and simple pulverizer. P9 emphasized the effect of a different combination of machines on particle size, energy, color, moisture, fat, and fiber content of ground chili. A combination of pin mill (one pass without screen) and plate mill (two passes) gives the best color chill powder with lower particle and energy consumption and higher fat content and fiber. P19 and P20 received 23-grade points. Double-stage grinding gives better color, temperature reduction, volatile oil, oleoresin, and curcumin compounds than single-stage grinding. Further, volume and surface mean diameter was higher in single-stage grinding and increased with increased moisture content for both grinding (Choudhary et al., 2015). Balasubramanian et al. (2013) discussed particle size distribution with bond's index and kick's constant. Particle size, bonds work index, and kicks constant increase with moisture content and sieve size opening and varied from 0.21 mm to 0.29 mm, 0.086–0.312 kWh/kg, and 0.68 to 20.33 kWh/kg, respectively. Conversely, size reduction ratio (25.42–14.57) and grinding effectiveness (0.077–0.008) decrease with moisture content. P24 (Singh and Goswami, 2000) received 22-grade points and discussed clove grinding at a temperature below −50 °C shows no clogging of sieve, more volatile oil, and lower specific energy consumption. P7 and P14 received 21-grade points. Goswami and Singh (2003) reported that grinding time and power consumption increased as the moisture content increased from 10% to 20% for both grinding (cryogenic and ambient grinding). Singh et al. (2018) discussed bulk powder properties such as flowability bulk density and tapped density, Hausner ratio, particle size distribution, compressibility index, color, microstructural and mineral content. Publication P2, P4, P5, P10, P11, P12, P16, P23, P25, and P26 received between 10 and 20 grade points. Evaporative water-cooling grinding of chill significantly reduces temperature, retained capsicum, oleoresin, and color of grounded chili (Bandara et al., 2015a,b). Pesek et al. (1985) reported that cryo grinding has high volatile oil content and volatile compound in nutmeg, cinnamon, cumin, white pepper, and oregano compared to ambient grinding. Saxena et al. (2014) discussed the volatile oil, antioxidant properties, and flavor for different diverse coriander genotypes. Liu et al. (2013) showed that the concentration and percentage of aroma compounds are retained in cryogenic grounded pepper compared to ambient hammer grinding, which induces browning and oxidative decomposition due to high temperature. Two genotypes of cumin ground in ambient and cryogenic and compare the volatile oil, oleoresin, total phenolic, flavonoid content, and antioxidant properties. Results showed that these characteristics were higher in cryo-grounded powder for both genotypes. The finer powder was observed in the case of cryogenic grinding compared to that in ambient grinding (Sharma et al., 2014). Goswami and Singh (2003), discussed the effect of cryogrinding of cumin on grinding temperature, specific energy consumption, particle size, and bond work index. Barnwal et al. (2014b) reported that the thermal conductivity of the cryo-ground samples was higher than that of the ambient ground samples. Kuang et al. (2011) discussed the effect of ultra-fine grinding of cinnamon and clove in a ball mill on powder particle size and antibacterial properties of the powder and results depicted that ultra-fine grinding powder had strong antimicrobial activity activities.

5. Discussion

DEMATEL approach can handle complex relationships among different component systems and is successfully applied in the food processing Field (Gardas et al., 2018). This paper has successfully used the DEMATEL approach to identify cause and effect criteria among selected factors. The ranking of those factors and the relationship among those factors can easily be understood. But as the number of factors is higher, this approach cannot identify the absolute degree of relation between the factors. A similar observation was pointed out by Aghelie et al. (2016). These methods fail to give comprehensive understanding of these factors. Conversely, the attribute coding approach is simple and gives a more in-depth knowledge of different factors. The factors are summarized from all the published literature in spice grinding and thoroughly studied to provide them with rank. The addition of ranking from all the pieces of literature defines the importance of those factors (Kohli et al., 2015). Specific factors that are important but still considered to impact grinding are also covered in this approach.

Table 9
Comparison of conventional and cryogenic grinding.

Parameter	Convectional grinding	Cryogenic grinding	
Energy consumption	High	Low	Balasubramanian et al. (2016)
Grinding zone temperature	High	No	Goswami and Singh, 2003
Loss of volatile oil and compound	High	Negligible	Balasubramanian et al. (2016)
Grinding of soft material	Very difficult	Possible	Balasubramanian et al. (2012)
Air pollution	High	No	Balasubramanian et al. (2012)
Clogging and gumming of mill	High	No	Singh and Goswami (2000)
Particle size distribution	Uneven	Even	Meghwal and Goswami (2014)
Product color and aroma	Highly affected	Completely retained	Ghodki and Goswami, 2016
Product shelf life	Decreased	Increased	Liu et al. (2018)
Throughput	Low	High	Balasubramanian et al. (2012)
Microbial Load	Possible	Does not exist	Saxena et al. (2015)
Nutraceutical benefits	Degraded	Retained	Meghwal and Goswami (2014)
Initial cost	Low	High	Wilczek et al. (2004)
Operating cost	Low	High	Wilczek et al. (2001)

The advantages and disadvantages of conventional grinding and cryogrinding are summarized in Table 9. The grinding loss of volatile oil and the essential compound is linked with an increase in grinding zone temperature. At higher temperatures, volatile oil and its flavoring compounds are evaporated due to the low boiling point of these compounds (Ghodki and Goswami, 2016). The grinding method and improved grinding techniques significantly affect the retention of volatile oil and its flavoring compounds. Cryogenic grinding shows higher retention of these compounds compared with other grinding methods. Singh and Goswami (2000) reported that clove was ground at a temperature below −50 ^{0}C without accumulation over the sieve and gives 29.5% more volatile oil compared to ambient grinding. The increase in the ground temperature of clove in the cryogenic range (- 110 to −50 ^{0}C) had no significant effect on volatile oil content. In an ambient grinding, an increase in temperature (55–85 ^{0}C) significantly reduced the volatile oil content. Similarly, nutmeg's volatile oil and oleoresin content were substantially different from ambient grinding to chilled and nitrogen grinding but not significant from chilled to nitrogen (McKee et al., 1993). In contrast to the above observation, Murthy et al. (1996) reported that in cryogenic grinding, decrease in temperature (−50 to −120 ^{0}C), there was an increase in the percentage of retention oil from 1.35% to 1.91%. Compared to ambient grinding, cryogenic grinding shows higher retention of volatile oil, 62.56% more in cumin powder (Saxena et al., 2018), 32% more in caraway seed (Wolf and Pahl, 1990), 129.5% in clove powder (Balasubramanian et al., 2012), oleoresin (87–90%) and curcumin (76–79%) (Barnwal et al., 2016). Similar results were observed in nutmeg (McKee et al., 1993), coriander (Saxena et al., 2014), nutmeg, cinnamon, cumin, white pepper, and oregano (Pesek et al., 1985).

Essential oil content varies with cultivar despite cryo or non-cryogenically ground powder. Saxena et al., 2014a and 2015 reported that south Indian varieties show higher oil content than north Indian varieties. Irrespective of varieties, cryogrinding shows a significant increase in volatile oil and its compound (linalool, α-Pinene, and geranyl acetate), and antioxidant properties compared to ambient grinding. Lower variation in geranyl methanoate content of ambient and cryo-grounded samples from north Indian varieties compare to south Indian varieties. Similar results for cumin genotype GC-4 and RZ-209 show 33.9 and 43.5% higher volatile in cryogrinding than the ambient grinding (Sharma et al., 2014). Recovery of volatiles is more in cryogenic grinding for all genotypes. In addition to these, particle size had a significant effect on the retention of volatile oil. Finer particle shows a higher percentage of retention of volatile oil than coarse particle size (Saxena et al., 2014). An increase in sieve size from 0.8 mm to 1.6 mm shows a decrease in retention of volatile oil 3.3%–2.93% (Saxena et al., 2014). Finer particles with higher surface area and homogeneity in particle size distribution release more volatile oil than coarse particles.

In improved grinding, chilled water circulation at 5 ^{0}C retained 2.5% more volatile oil than ambient grinding (Shanmugasundaram et al., 2018). Choudhary et al. (2015) emphasized that double-stage grinding had 15–25% more volatile oil, active oleoresin compounds, curcumin, and fine turmeric powder than single-stage. Ultra-low temperature (−3.33 to −1.25 °C) has a significant effect on retention of volatile oil (17%), oleoresin (2%–3%) content with a 2–3% increase in moisture content of powder (Mathew and Sreenarayanan, 2007). Evaporative cooled grinding increases the 50% higher retention of capsicum oleoresin than ambient grinding.

Energy consumption varied with grinding methods, moisture content, speed, feed rate, and sieve size. Balasubramanian et al. (2013) reported that specific energy consumptions showed a reducing trend (310.71–30.55 kJ/kg) with increasing feed rate but the increasing trend with moisture content and sieve size openings. Rotor speed was a major contributor to specific energy consumption, followed by feed rate and sieve size. The specific energy consumption varied from 62 to 85 kJ/kg with an increased feed rate from 1.5 to 6 kg/h with −110 ^{0}C grinding temperature, 69 m/s rotor speed, and 0.5 mm of sieve opening (Singh and Goswami, 2000). Similarly, Goswami and Singh (2003) reported that grinding time and power consumption increased with increased moisture content from 10% to 20% for grinding (ambient and cryogenic grinding). Still, this increase was inclined more towards ambient grinding. Material with high moisture content behaves plastic or ductile (water acts as a plasticizer), responsible for high energy consumption. Similar results were observed in soybean grinding (Lee et al., 2013) and balloon flower grinding (Moon and Yoon, 2018). Grinding constants in grinding laws are associated with energy requirements in the grinding process. Lower values of grinding constant show lower energy requirement (Jung et al., 2018). Low moisture content and brittle nature of sample show lower values of grinding constant (Balasubramanian et al., 2013). Energy consumption was varied with different grinding temperatures. Mathew and Sreenarayanan (2007) reported that Grinding under ambient condition, low temperature and ultra-low (Dry ice) increased temperature from 40.30 to 47.45 °C, 21.2°C to 39.95 and −3.33 °C–23.13 °C, respectively. An increase in grinding zone temperature will increase the grinding time (155–245 s) and specific energy (24.79–46.62 kJ/kg°C). Energy consumption is related to the brittle nature of the material. More brittle sample, less energy is required to rupture the material, whereas in ambient grinding opposite trend was observed. In ambient grinding, the material behaves like elastic and makes the grinder sticky resulting sieve clogging (Meghwal and Goswami, 2013). Grinding method also influences the energy consumption pattern. Specific power consumption (kWh/kg) for ambient and cryogenic grinding in rotor mill for fenugreek (0.0071 and 0.0071) and pepper (0.0031 and 0.0169), for ball (0275 and 0.0265) and (0.0297 and 0.0235), for hammer (0.0792 and 0.0558) and (0.0551 and 0.0419) and for pin mill (0.0817 and 0.0614) and (0.0623 and 0.0509) were observed (Meghwal and Goswami, 2014).

In improved grinding methods, chilled water circulation at 5 ^{0}C increased energy consumption from 37 Wh energy to 62 Wh energy in ambient grinding. (Shanmugasundaram et al., 2018). Power consumption varies with the grinding techniques. Meghwal and Goswami (2014) reported high power consumption in pin mills followed by hammer mills, rotor mill, and ball mill. The temperature rises in ambient and cryogrinding are high in pin followed by hammer, rotor, and ball mill. Among 12 different combinations of milling for chili grinding, A combination of pin mill (one pass without screen) and plate mill (two-pass) recoreded the best color chill powder with a particle size of less than 500 μm and energy consumption of 0.095 kWh/kg (Bandara et al., 2015b).

Different superfine grinding technologies have been developed based on materials, such as jet mill, cryogenic grinding, vacuum grinding, ball milling, colloid mill, and roller grinding (Chen et al., 2017). Prevention of oxidation and volatilization of components during grinding is an important consideration. Except jet milling and cryogenic grinding, other grinding methods resulted in increased temperature, consequently oxidation and volatilization, and were suitable for specific types of products (Gao et al., 2020). Jet milling is another promising technology and competitive to cryogenic grinding. Spraying material through a nozzle using compressed air (or inert gas nitrogen) resulted in high-speed collision and impact against solid milling surface results in size reduction (Chamayou and Dodds, 2007). Characteristics of jet milling are uniform fine particles, a very low rise of temperature in the grinding zone due to the Joules Thompson effect, and suitable for thermosensitive products (Karam et al., 2016). Recently, studies have focused on wheat (Lazaridou et al., 2018), Lentinus edodes stem (Gao et al., 2010), and defatted soybean (Muttakin et al., 2015). The great hindrance in jet milling is its higher energy consumption compared with other grinding methods. Efforts are required to improve this machine to decrease energy cost and use in spice grinding along with liquid nitrogen treatment or chilled compress air.

Particle size is important in food preparation and other applications in many industries. Grinding can produce micron, submicron, and even nano-sized particles, which has gained more importance from researchers and industry. Particle size reduction can change the material structure and chemical activities, which have outstanding characteristics in commercial applications (Huang et al., 2018). Meghwal and Goswami (2014) reported that surface area is affected by grinding methods. The specific surface area was observed high in rotor mill followed by hammer mill, pin mill, and ball mill. Similar results were observed for pepper powder. The temperature has a significant effect on particle size. The volume mean diameter of cryo-grounded cumin at different temperatures i.e. −100 ^{0}C, −40 ^{0}C, and 30 ^{0}C were 94.63 μm, 139.5 μm, and 158.2 μm, respectively (Goswami and Singh, 2003). Cryogrounded turmeric shows 50 μm smaller particle size than ambient grinding. Maximum particle sizes of 472 μm in ambient grinding and 296 μm in cryogenic grinding were observed (Manohar and Sridhar, 2001). Similar results were observed for black pepper grinding; an increase in temperature −3.33 to 12.86 °C showed increases (0.15 mm–0.18 mm) in volume surface mean diameter (Mathew and Sreenarayanan, 2007). Grinding temperature is related to the material's brittleness; at higher temperatures, there was a decrease in brittleness. Treatment with liquid nitrogen increases the material's brittleness, which ultimately affects particle size (Saxena et al., 2018). Similar characteristics of the particle size distribution were observed in coriander powder (Balasubramanian et al., 2016), coriander, fenugreek and black pepper powder (Barnwal et al., 2014a), Turmeric powder (Barnwal et al., 2014b), black pepper (Meghwal and Goswami, 2017), chili powder (Singh et al., 2018). Similarly, Goswami and Singh (2003) reported an increase in specific surface area of fenugreek seeds with increasing moisture content, but this increase was inclined more towards cryogenic grinding. In contrast, larger particle sizes in soybean grinding (Lee et al., 203) and balloon flower grinding (Moon and Yoon,

2018) were observed due to decreased brittleness. Particle size uniformity and distribution were achieved higher in cryogenic grinding and super fine grinding (Liu et al., 2013). Conversely, conventional grinding results in a mixture of coarse and fine particles. Particle size is reduced by increasing milling time through different sieve sizes. Increased grinding time increases the shear stress, and ultimately it affects wear and grinding zone temperature (Stenger and Peukert, 2003).

Color is an important indicator of sensory evaluation and consumer preference (Gao et al., 2020). The L* value signifies the color brightness and varied from 0 (darkness) to 100 (whiteness); a* value indicates the redness or greenness, and the b* value represents the yellowness or blueness of the samples. In addition to this, the total color difference (ΔE), chroma (C), hue angle (α0), and browning index (BI) can be calculated from the L*, a*, and b* values (Meng et al., 2017). Grinding zone temperature would accelerate the degradation of color pigments and chemical oxidation, ultimately affecting powder color. Granularity and grinding zone temperature had a significant effect on the color of powders such as red pepper powder (Chen et al., 2015), turmeric powder (Choudhary et al., 2015), chili powder (Singh et al., 2018). Mallappa et al. (2015) found that Values of L*, a*, and b* (40.15, 33.66, and 37.28) increased in cryoground byadagi chili powder as compared with convectional spice pulverizer (35.84, 30.09, and 31.39). Similar increases in king chili's redness (a value) were observed in cryogenic grinding (Singh et al., 2018). Cryogenic grinding retains the product color in fenugreek powder (Meghwal and Goswami, 2014), coriander powder (Saxena et al., 2015), and black pepper powder (Ghodki and Goswami, 2016). A significant color change was observed in improved grinding under evaporative cooled grinding (Bandara et al., 2015a). In convectional grinding, change in L*, a*, and b* values are significantly dependent on grinding methods and raw material moisture content. The Browning index of coriander was higher in higher moisture content hammer mill grinding than pin mill (Barnwal et al., 2015).

Antioxidant, anti-bacterial, anti-proliferative, anti-tumor, cholesterol-lowering, and other medicinal properties are related to the physicochemical and nutraceutical compounds present in spices. The grinding method and subsequent storage of ground products significantly affected the chemical composition of spices (Liu et al., 2018). The chemical composition and nutraceutical compounds with their medicinal benefits are summarized in Table 10. These components are located in cell-matrix and can be easily made available after grinding. Further, grinding enhances the bioaccessibility i.e., release and adsorption, improves the protein and polysaccharide solubility (Zhang et al., 2012), improves extraction efficiencies (Chou et al., 2016), influences total phenolics and flavonoids content(Zhao et al., 2015), can alter the dietary fiber matrix and changing the antioxidant activity of powders (Zhu et al., 2010). Croygrounded coriander powder shows 60–70% higher total antioxidant than ambient ground powder. Phenols, flavonoids, and antioxidant activity enhanced in all genotypes of coriander grounded in a cryogenic grinder (Saxena et al., 2014). A similar trend was observed in cryo-grounded cumin powder, with 20–25% higher DPPH scavenging activity than convectional grounded powder (Sharma et al., 2014). Cryogenic grinding of pepper improves the chemical quality (Liu et al., 2018). In conventional grinding, a rapid increase in grinding zone temperature leads to loss of total phenolic and flavonoids (Liu et al., 2013). Mineral composition, especially calcium and iron in cryo-grounded king chili, was significantly higher (9.36 by wt% and 3.51 by at. %) than convectional grinding (Singh et al., 2018). Cryogenic grinding enhances the mineral and other chemical compounds. The cryo-grounded powder may be used for extracting the mineral and other chemical compounds.

Grinding also modifies physicochemical properties like thermostability (Zhang et al., 2020), and crystallinity (Huang et al., 2018). The grinding method had a significant effect on specific heat, thermal conductivity, and thermal diffusivity. In Cryo grinding and ambient grinding, specific heat (10.45–16.26 kJ/kg K and 10.36–14.22 kJ/kg K), thermal conductivity (0.049–0.059 W/mK and 0.051–0.077 W/mK) and thermal diffusivity (1.02×10^{-8} to 1.08×10^{-8} m^2/s and 0.93×10^{-8} to 1.20×10^{-8} m^2/s) increased, respectively (Barnwal et al., 2016). A similar result was observed in hammer and mill pin ground coriander powder; specific heat was increased from 12.25 to 22.64 kJ/kg K. Specific heat is significantly affected by grinding methods, temperature, and moisture content (Barnwal et al., 2015). Cryogrinding shows higher thermal conductivity because of the inert atmosphere (Singh and Goswami, 1999). Better retention of physicochemical properties, better sensory characteristics, flavor, aroma, and taste was observed in reduced temperature grinding methods (Liu et al., 2013). The cryogenically grounded powder had a regular, smaller, smooth size and was shaped with higher bulk and tap density and low compressibility index and Hausner ratio compared to ambient grounded powder (Singh et al., 2018).

Considering the representation made using different approaches and in-depth study of those factors it is intended to guide the various members in understanding spice grinding and its importance.

6. Challenges and future needs

As discussed above, cryogenic grinding is an advanced grinding technology to produce quality spice powder with magnificent performances. Despite several advantages, there are still additional challenges that remain. Most of the researchers had worked on cryogenic grinding technology. In an optimized mill, 1 kg grinding of material required a 0.6–4 kg liquid nitrogen (Liang and Hao, 2000). Apart from several economic advantages of liquid nitrogen, energy consumption and cost of cold agents significantly affect the operation cost and actual consumption of liquid nitrogen is double in plants. The cost of nitrogen alone takes over 40% of the cost of cryogenic grinding (Wilczek et al., 2001). For many materials, the supply of cold temperature is not necessarily −195.6°C (Wilczek et al., 2004). No in-depth study has been observed in spice grinding on how much temperature is required to make feed material brittle. Precise measurement of glass transition temperature and state diagram is ideal for preventing excess consumption of liquid nitrogen. Optimization of liquid nitrogen is of utmost importance by using new processes and new cooling equipment. Cryogenic grinding is not about just using liquid nitrogen; it is the overall optimization of process variables like moisture content, grinding types, feed rate, sieve selection, and speed of the rotor. Most researchers have worked on the lab-scale model. However, the initial investment, operation cost and advancement or optimization of the process, and commercial scale-up of models are not presented very well. In cryogenic grinding, proper precautions and safety measures should follow; otherwise, it can seriously affect health problems (Ali et al., 2021). Other than cryogenic grinding, some researchers tried alternative solutions like double stage grinding, cooling evaporator on grinding chamber, prechilling, water jacket, and dry ice. A detailed investigation is required in these alternative techniques.

6.1. Post-processing

Spice grinding has a significant impact on the physical and chemical properties of powders. Finer particles may affect the hydration and absorption properties. Water and oxygen absorption rate may enhance, which quickly causes the undesirable oxidation of valuable components (Gao et al., 2020). Storage under ambient and poor packaging, the cryogenic powder becomes more unstable than convectional grounded powder (Liu et al., 2013). Proper attention should be given to the spice powder packaging and storage environment.

6.2. Dust problem

Dust is another severe issue emerging from spice grinding. A particle size of fewer than 420 μm can cause health-related issues and fire explosion problems (Gao et al., 2020). Dust emission may cause wear and damage to equipment, loss of material, unpleasant smell, and workers'

Table 10
Chemical composition and health benefits of selected Indian spices.

Spices	Chemical Composition and Compounds		Health benefits	References
Fenugreek	Protein: 20–26%, fat: 6–7%, carbohydrates:50–60% (dietary fibre), ash -3-5%, minerals: < 1%, fatty acid: (palmitic: 8–11%, stearic: 3–5%, arachidic: 1–2%, oleic: 30–35%, linoleic: 30–45%, and α-linolenic: 12–28%), Seed oil content: 3–7% among 46 genotypes of fenugreek	Alkaloids (betain, choline, trimethylamine, gentianine trigonelline, and carpaine) Amino acids (lysine, l-tryptophan, arginine, histidine, isoleucine, leucine, 4 hydroxyisoleucine), saponins and steroidal sapinogens	Hypoglycaemic and hypocholesterolaemia effect, immunomodulatory, prevents asthma, emphysema, vomiting, fever, pneumonia, digestive effect decreases blood pressure, prevents constipation, anti-ulcer and cancer agent	Khorshidian et al. (2016); Wani and Kumar (2018)
Pepper	Protein: 11–14%, fat: 6–7%, crude fibre 8–20%, total ash 3–7%,starch:28–49%, alkaloids: 5–9%, volatile oil: 1.2–5% (piperine-1.7–7.4%, α-pinene (4–7%), β-pinene -9–11%, sabinene-9-18%, limonene-20-22%) and β-caryophyllene-20-28%)	Piperine (piperetine, piperanine, piperylin a, piperolein b and pipericine) Camphene, carvone, δ-3-carene, α-phellandrene, p-cymene, β-bisabole, limonene, cis-carveol, carvacrol, camphor, myrcene, cis-ocimene,8-cineole, β-phellandrene, α-pinene, β-pinene, borneol, trans-carveol, carventanacetone, 1, β-caryophyllene	Anti-oxidant, anti-tumor, anti-bacterial, cholesterol-lowering properties	Al-Jasass and Al-Jasser (2012); Ashokkumar et al. (2021)
Coriander (*C. sativum* L.)	Protein: 10–15%, ash: 5–10%, crude fibre 20–30%, volatile oil 0.2%–2.6% and fat oil 13%–20%, fat oil (petroselinum acid:67–70%, linoleic acid:14–17%, oleic acid:5–8% and palmitic acid:2–4%), Volatile oil (linalool:60–80%, geraniol:1%–5%, terpinen-4-ol:2–3%),γ terpinene:1–8%, limonene:0.5%–4.0%, a-pinene:0.2%–8.5%, myrcene: 0.2%–2.0%, camphor: 0.9%–4.9%, esters geranyl acetate; 0.1%–4.7%	carvone, geraniol, limonene, borneol, camphor, elemol, Sterols, Tocols	Digestive, tonic, carminative, diuretic, aphrodisiac, stimulant, stomachic, analgesic, anti-inflammatory, antioxidant, anti-aspergillus activity	Mandal and Mandal (2015); Msaada et al. (2007)
Black cumin	Protein: 20–30%, crude fiber: 8–40%, ash: 3.7–4.9%, fixed oil: 30–40%, volatile oil: 2.3–4.5%, fatty oil: (linoleic acid:50%–60%, oleic acid:15–20%, eicosadienoic acid:2–4%, and dihomolinoleic acid:8–12%, palmitic and stearic acids: up to 30%. A-sitosterol is the major sterol, accounting for 44%–54% of the total sterols followed by stigmasterol (7 %–22%) of total sterols	Arachidonic, eicosadienoic, linoleic, oleic, palmitic, stearic, myristic acid and beta-sitosterol, cycloeucalenol, cycloartenol, sterol esters, and sterol glucosides, nigellone, Thymoquinone, thymohydroquinone, dithymoquinone, thymol, carvacrol, α and β-pinene, d-limonene, d-citronellol, p-cymene, p-cymene, carvacrol, t-anethole, 4-terpineol and longifolen	Antidiabetic effects, anti-inflammatory effects, digestive stimulant action, gastroprotective effect, chemo preventive effects, immunomodulatory action, cardio-protective influence through hypolipidemic and hypotensive effects	Ahmad et al. (2013); Al-Jasass and Al-Jasser (2012)
Ajowan	Protein: 12–16%, Crude fibre: 8–12%, Carbohydrates:32–38%, Ash: 3.7–4.9%,Fat: 15–20%, Calcium:0.40–1.42%, phosphorus:0.20–0.30%, volatile oil: 2–4% (thymol 35–60%, p-cymene: 10–16%, terpinene 10–12%, pinene:4–5% and dipenene:4–6%.)	β-Pinene, ρ-cymene, myrcene, γ-terpinen, δ-3-carene, α-terpinene, terpinene-4-ol, β-phellandrene, terpinolene, thymol, carvacrol,	Antimicrobial, antirheumatic, diuretic, stimulant, carminative, and expectorant	Masoudi et al. (2002); Ramchander and Middha (2017)
Clove	Protein: 3.4–6%, crude fibre: 8–12%, carbohydrates:50–62%, fiber:30–34%, ash: 5–6%,fat:16–20%, potassium (1050–1200 mg/100 g)and magnesium (250–270 mg/100 g), essential oil:5–7% (M-eugenol:69–76%, eugenol acetate:10–13%), Tyranton:6–8% and caryophyllene:5–7%)	Eugenol, caryophyllene, α-caryophyllene eugenia caryophyllus.	Antioxidant activity, antihyperglycemic activity, antiseptic, anesthetic, analgesic, anti-inflammatory, and antimicrobial activities, blood purifier, cancer prevention, powerful germicidal properties	Al-Jasass and Al-Jasser (2012); Cortés-Rojas et al. (2014)
Cinnamon	Protein:2–5%, crude fibre: 25–35%, carbohydrates:50–60%, ash: 5–6%, fat:16–20%, mineral: iron, zinc and calcium, manganese, potassium and phosphorus (7.0, 2.6, 83.8, 20.1,85.5, and 134.7 mg/g) respectively. Essential oil: up to 2% (cinnamaldehyde, eugenol: 60–80%) and minor trans-cinnamic acid, o -methoxy cinnamaldehyde, eugenol, and monoterpenoids: 49.9–62.8%)	Procyanidins, diterpenes, phenylpropanoids, mucilage, polysaccharide, cinnamate, procyanidins, and catechins	Antioxidant activity, anti-inflammatory, lower hepatic cholesterol, and triglyceride level, antibacterial activity , antidiabetic, anticancer, lipid-lowering, and cardiovascular-disease-lowering compound, activities against parkinson's and alzheimer's diseases	Ranasinghe et al. (2013); Rao and Gan (2014)
Cumin (*Cuminum cyminum*)	Protein: 15–20%, dietary fibre: 2.5–5.5%, fiber: 1–4%, ash: 5–6%, fat:8–10%, vitamins such as thiamine riboflavin and niacin 0.05, 0.28 and 2.7 mg/100 g, respectively). Mineral: iron (6.0) and zinc (6.5) (mg/100 g), volatile oils (1–5%) 37 compounds representing a total of 95–99% of all volatiles - aldehyde (36–40%) and remaining β-pinene, p-cymene and γ-terpinene (56–60%)	β-pinene, p-cymene, γ -terpene, cuminaldehyde, phellandral, cuminyl alcohol, perillaldehyde, luteolin, catechin, gallic acid, coumarin, quercetin, apigenin, anthraquinone, cinnamic, glycoside, resin, saponin, tannin, and steroid	Antioxidant activity, anticancer effects, antimicrobial activity, antidiabetic, antispasmodic, carminative, digestive stimulant, nervous and immune system, and chemoprotective activity	Allaq et al. (2020); Sowbhagya (2013)
Turmeric	Protein: 8–10%, crude fiber: 5–7%, carbohydrates:50–70%, ash:2–3%, fat:4–8%, essential oil (4–5%), mineral composition: calcium:0.20–0.40%, phosphorus: 0.30 0.80%, potassium:0.20–0.50%, iron:0.02–0.07%,alkaloid:0.58–0.76%,	Curcuminoids (curcumin, demethoxycurcumin and bisdemethoxycurcumin), ar-turmerone, α and β-turmerone	Anti-inflammatory, diuretic, laxative, good for affections of the liver, jaundice, diseases of the blood, antimicrobial, antioxidative, anti-alzheimer, antitumor, and anticancer potentials	Meng et al. (2018); Niranjan and Prakash (2008)

(*continued on next page*)

Table 10 (*continued*)

Spices	Chemical Composition and Compounds		Health benefits	References
	saponin:0.35–0.45%, tannin:0.8–1.20%, sterol:0.01–0.05%, phytic acid:0.40–0.90%, flavonoid:0.35–0.40% and phenol:0.04–0.08%, oleoresins(aromatic-turmerone: 8–10%, alpha-santalene:7–8% and alpha-turmerone: 5–7%)			
Fennel	Protein: 5–10%, fat: 8–10%, fiber: 15–20%, ash: 10–12, nitrogen free extract: 40–45%. Minerals; potassium (820–860), calcium (540–590), manganese (200–220), sodium (15–20) and iron (7–10) mg/100 g. Essential oil 2–4% (trans-anethole:28–32%,2-pentanone: 20–25%, fenchone: 9–11% and benzaldehyde-4-methoxy:7–9%)	β-pinene, estragole, limonene anethole, R-pinene, β-myrcene and p-cymene	Hepatoprotective effect antioxidant activity, antithrombotic activity, anti-inflammatory activity, antidiabetic activity, antitumor activity, acaricidal activity, antibacterial activity	Bukhari et al. (2014); Malhotra (2012)

health issues are a significant concern. Specific health issues related to dust are cardiovascular, diabetes, neurodegenerative, lung scarring, and fibrosis diseases (Zheng et al., 2016). Particular attention should be given to maintaining a clean environment during spice grinding.

6.3. Laboratory versus industrial application

In spice grinding, superfine, cryogenic, and improved grinding methods are done on a laboratory scale. In actual industrial applications, the scale of those technologies faced specific challenges. Detailed research is required to convert these lab-scale technologies into industrial-scale production with optimized production and processing cost and lower energy consumption.

6.4. Insufficient fundamental and systematic research

Each grinding techniques produce powders of different physical and chemical properties. Spice powder may be used as the end or intermediate product, especially extracting valuable and medicinal components. These grinding techniques may affect physicochemical properties and physiological activities. There are few reports available on these aspects. It is indeed the need of the hour to understand all aspects of spice processing from drying to storage. Each unit operation is closely related to other and affects the final quality of spice powder.

7. Benefits of attribute coding

Stakeholders like researchers, engineers, manufacturers, industries, small associations, SGHs, and small and medium entrepreneurs can be benefited by using these coding tables as per their specific requirements.

7.1. For researchers

Selection and optimization of operational parameters, design issues can be easily obtained from the table. With the help of this quick understanding attribute table, researchers/scientists can focus on an alternative for liquid nitrogen, multistage grinding, and new techniques for further studies.

7.2. For engineers

The simple machine cannot perform all the operations effectively, so automation controls different parameters. For developing a spice grinding process, optimizing machine parameters like feed rate, sieve size, speed, and the energy consumption is vital for designing and modifying an existing machine. Grinding zone temperature is the main problem in existing grinding machines. The designer/engineer needs to focus on specific design aspects like grinding stages, grinding time, and the grinding mechanism that reduces the grinding zone temperature and improvement of existing technologies. The developed mill will be evaluated for its performance and operational economics compared to conventional grinding methods, and operating parameters shall be optimized for better performance.

7.3. For manufacturers/Industries

Manufacturers can take advantage of manufacturing the best grinding machine considering end product, end-user, total cost, and variable cost. The quantification and monitoring of the influential attributes help closely control them to precisely fulfill the user demand. Moreover, market trend by observing the attributes magnitudes helps them understand the kind of machine used and its effect on end-product characteristics. Manufactures can improve grinding machines for spices against existing conventional multipurpose grinding for wheat, rice, millet, pulses, and spices.

7.4. Usefulness to the other stakeholders

Spice growing farmers and small associations and small and medium entrepreneurs will be benefited from the importance of attribute coding to optimize operational parameters and variables to reduce processing costs and get a premium quality product.

8. Conclusions

In the present study, twelve factors under cause and thirteen factors under effect were identified using systematic review and expert view. The identified factors are expressed and analyzed to establish the relationship between identified factors and the role of each factor using DEMATEL and an attribute-based coding approach. The results highlighted that grinding meth (7.37), liquid nitrogen treatment (7.06), moisture content (6.12), feed rate (5.47), and sieve type(4.23) were the most critical factors with high-grade points and need much attention. The attribute-based coding approach identified the same factors with grade points of (95, 80, 45, 39, and 31). Although in the attribute coding approach, an in-depth understanding of those factors was summarized and presented very well. Factors identified under improved grinding methods like water jacket, chilling, dry ice, and stage grinding also show promising results in spice grinding and are very well observed in the attribute coding approach. Specific challenges in cryogenic grinding for design modification, liquid nitrogen use efficiency, and cost reduction may gain more importance in practical application in spice grinding. Various stakeholders like researchers/scientists, breeders, designers/engineers, manufacturers, entrepreneurs, and industry can be benefitted by identifying research gaps, opportunities, challenges, and perspectives of different grinding techniques. Considering the current situation in production, processing, and increasing demand for quality spices from consumers, there is a need to develop a suitable and sustainable grinding technology for spices.

Conflict of Interest

The Authors declare no Conflict of Interest.

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