




## Unveiling moisture effects on physical, fluid, and thermal dynamics of fennel seeds

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**Abstract.** A phytochemical analysis of three varieties of seeds, AF-1, AF-2, and AF-3, suggested the highest protein content for the AF-2 variety, equivalent to 15.69%. The highest crude nitrogen content was found for the AF-2 variety. The pH value for the AF-1, AF-2, and AF-3 varieties was 5.84, 5.9, and 5.98, respectively. The AF-2 variety was also found to have the lowest  $a^*$  value of -0.0533; hence, they were greener than the AF-1 and AF-2 varieties. Analysis of physical and thermal properties was done by varying the moisture level of the seeds from 10 to 22%. The gravimetric properties, including bulk density and true density, decreased with the increase in the moisture content from: 379.867 to 312.5, 370.37 to 329.75, and from 348.93 to 306.19 kg m<sup>-3</sup> for the AF-1, AF-2, and AF-3 varieties. True density decreased from 1000 to 666.66 kg m<sup>-3</sup>. Angle of repose increased from 79.38 to 82.24° for the AF-1 variety, from 79.14 to 82.18° for the AF-2 variety, and from 79.82 to 81.88° for the AF-3 variety. The coefficient of friction increased with the moisture level; however, it was found to be the highest for the wood surface for all three varieties of fennel seeds. Specific heat and thermal conductivity increased significantly with the increase in moisture. The knowledge of the physical properties of the fennel seeds, including their size, shape, volume, and surface area, is helpful in designing machinery for sorting, grading, and sizing. Gravimetric properties like bulk density, true density, and porosity aid in designing storage containers, hoppers, and separation processes based on density. Frictional properties like the coefficient of friction and angle of repose play an essential role in designing storage bins, chutes, and handling equipment, including screw conveyors, threshers, and forage harvesters, to ensure smooth movement and prevent blockages. Drag properties like terminal velocity, drag coefficient,

and projected area are useful for the design of separation systems, like air classifiers, which sort grains and seeds according to their aerodynamic characteristics. Thermal properties help design the equipment used in heat transfer processes like cooking and drying. It also helps in understanding the heat transfer phenomenon in the food system.

**Key words:** density dynamics, drag properties, fennel seeds, moisture content, thermal metrics, varietal analysis

### 1. INTRODUCTION

The fennel plant consists of finely dissected, fern-like leaves and clusters of yellow flowers organised in compound umbels (Wilson, 2016). India, Russia, Germany, France, Italy, Argentina, and the United States are the top countries for fennel cultivation worldwide in temperate and subtropical climates. Regions like Rajasthan, Gujarat, Uttar Pradesh, and Punjab are mostly known to grow fennel seed plants (Ram *et al.*, 2022). Fennel plants thrive in areas characterised by a semi-arid to arid climate. They grow in well-draining soil and demonstrate resilience in hot and dry conditions, rendering them well-suited for cultivation in regions of India and the world that experience such climates. Fennel is mainly grown as an annual crop in India. Fennel seeds are often sown in India in winter, particularly in October and November. In the field, the seeds are sown immediately, and germination usually takes place within a few weeks (Anitha and Hore, 2018).

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In the summer, from March to May, fennel plants blossom and produce seeds, and the seeds are ready to be harvested. Fennel seeds have almost 1-6% of essential oils. The primary constituents of these essential oils are anethole, fenchone, and limonene. Fennel seeds contain significant amounts of bioactive compounds such as polyphenolic compounds, notably flavonoids and phenolic acids (Lekhvar *et al.*, 2025), as well as carbohydrates, proteins, and dietary fibre. Additionally, they are abundant in minerals, including significant levels of potassium, magnesium, and calcium (Dong *et al.*, 2022).

Fennel seeds are renowned for their sweet, liquorice-like flavour and aromatic qualities. They are utilised in various culinary applications, such as seasoning meats, enhancing the flavour of bread and baked goods, and contributing to the complexity of spice blends. Fennel seeds are used to flavour liqueurs, confectionery, and pickles (Guidi and Landi, 2014). Several research investigations have focused on the pharmacological and therapeutic properties of fennel seeds, specifically anethole, which is the major constituent of its essential oil. Studies have examined their effects on various medical issues, such as dysmenorrhea and gastrointestinal diseases, as well as their potential antibacterial actions (Noreen *et al.*, 2023). Fennel seeds possess a diverse chemical composition and offer valuable cooking, medicinal, and therapeutic applications, making them an invaluable natural asset. They are a subject of ongoing scientific interest and investigation because of their distinctive flavour, fragrant qualities, and historical relevance (Rather *et al.*, 2016). The powder formation from the seed is the mechanical process of size reduction. In contrast, this process is related to the gradual increase in the temperature within the grinding machine from ambient room temperature of 35 to 95°C. However, this temperature increase may have a negative impact on the quality of the final product, *i.e.* fennel seed powder (Singh and Meghwal, 2020). In particular, it may result in the breakdown of heat-sensitive aromatic chemicals crucial for the distinctive flavour of fennel plants. Cryogenic grinding systems are a unique technique established to maintain the high quality of fennel seed powder by carrying out the grinding operation at very low temperatures (Kaur and Srivastav, 2018). Additionally, in-depth knowledge of the physical, chemical, and thermal properties of fennel seeds is necessary for the construction of such a cryogenic grinding machine. For evaluating the heat transfer process inside the grinding system, specific heat, which measures the amount of heat needed to raise the temperature of a unit mass of fennel seeds by a specific amount, is essential. For modelling heat transfer processes during grinding operations, bulk thermal diffusivity and bulk thermal conductivity, which describe the capability of a material to conduct and transmit heat, are equally crucial factors (Yu *et al.*, 2015). While many studies have been done on the physical and thermal characteristics of seed spices, including cumin, coriander, black pepper, and fenu-

greek, the volume of work, particularly on fennel seeds, is noticeably small. To fill in this information gap and learn how the physical and thermal characteristics of fennel seeds alter in response to changes in moisture content, as well as to identify the physicochemical characteristics of the different varieties of fennel seeds, extensive experiments are required. Moisture content becomes a crucial variable that affects almost every aspect of seed processing. It impacts the utilisation of machinery and equipment for planting, moving, processing, storing, and extracting oil. It also has a big impact on how long fennel seeds stay fresh. In India, diverse varieties have been released commercially for cultivation throughout the country. The adaptability of different varieties depends on both climatic conditions and soil type. Ajmer Fennel-1 (AF-1) was developed by the ICAR NRCSS, Ajmer (Rajasthan), and was released in 2005 as a rabi crop. This variety is erect and tall-growing, bearing large, umbellate flowers. The AF-1 variety of fennel seeds has an average yield of 2000-2200 kg ha<sup>-1</sup> during the rabi season and 2510 kg ha<sup>-1</sup> when grown as an early transplanted crop. It has tolerance to *Ramularia* and *Alternaria* blight. The Ajmer Fennel-2 (AF-2) variety was developed by the ICAR NRCSS, Ajmer (Rajasthan), and was released in 2017 as a rabi crop. It yields an average of 1790 kg ha<sup>-1</sup> during the rabi season. This variety has tolerance to *Ramularia* and *Alternaria* blight. The Ajmer Fennel-3 (AF-3) variety was developed by the ICAR NRCSS, Ajmer (Rajasthan), and was released in 2018 for cultivation as both an early sowing and a rabi crop. It yields an average of 2140 kg ha<sup>-1</sup> during the rabi season and exhibits tolerance to *Ramularia* blight (Sable *et al.*, 2023). These developed varieties of fennel seeds have been found to be high-yielding and resistant to pests, making them more suitable for market sales while ensuring the availability of improved quality to consumers; therefore, research on these varieties is becoming significant. The goal of this study is to fill the existing gaps by examining how variations in moisture content affect the physical and thermal characteristics of different fennel seeds, as well as to estimate the physicochemical parameters of the three varieties of fennel seeds. The obtained information is useful for the preparation, storage, and consumption of fennel seeds.

## 2. MATERIAL AND METHODS

### 2.1. Sample preparation

The three varieties of fennel seeds used in the research, AF-1, AF-2, and AF-3, were procured from the NRCSS, Ajmer, India, in March 2024, and are shown in Fig. 1. The cultivation of the fennel seed crop requires well-prepared land achieved by ploughing. The ploughed field is levelled by planking to increase the fineness of the soil. Fennel is grown in cooler temperatures; therefore, cultivation typically begins in October and lasts until the first week of November (Sable *et al.*, 2023). The seed samples



**Fig. 1.** Three varieties of fennel seeds: AF-1 – Ajmer fennel – 1, AF-2 – Ajmer fennel – 2, AF-3 – Ajmer fennel 3.

underwent a meticulous cleaning process, eliminating any traces of dust, dirt, twigs, and undesired damaged seeds. Subsequently, proximate analysis was conducted on the three fennel seed varieties to assess their physicochemical properties. This was followed by measuring pH, water activity, and colour characteristics. After the physicochemical analysis, the fennel seeds of the three varieties (AF-1, AF-2, and AF-3) were examined for their engineering and thermal characteristics while being conditioned at different moisture levels.

The initial moisture content of the seeds was determined by using the Dean and Stark apparatus (Clemenson *et al.*, 2012), where 20 g of seeds were added to 200 ml of toluene, and the moisture trapped in the condenser was finally measured. The initial moisture content of the fennel seeds was found to be 10.33% for the three varieties. Equation (1) was employed to establish different moisture levels within the samples of different seed varieties, established at 10, 14, 18, and 22%:

$$Q_{dw} = w_i \frac{(m_f - m_i)}{100 - m_f}, \quad (1)$$

where:  $Q_{dw}$  – quantity of distilled water (g),  $m_f$  – final moisture content of the sample (%),  $m_i$  – initial moisture content of the sample (%), and  $w_i$  – initial weight of the sample (g).

The sample was stored at 4°C in the refrigerator for two weeks in zipped polyethylene bags. The sample prepared in this manner served as the basis for examining the engineering and thermal characteristics of the fennel seeds under varying moisture conditions. The experiments were replicated three times for each set of tests.

## 2.2. Physicochemical properties

To determine the physicochemical properties of the fennel seeds, proximate analyses of the three varieties of the fennel seeds were conducted, followed by the determination of the pH and water activity.

### 2.2.1. Proximate analysis

The proximate analysis of the three varieties of the fennel seeds was conducted, where the parameters estimated are represented as shown in Table 1, along with the instruments utilised.

### 2.2.2. pH

The pH levels were determined using the method described by Rahman *et al.* (2021). Fennel extract was prepared using 2 g of powdered samples mixed with 80 ml of distilled water, and this mixture was agitated in a shaker

**Table 1.** Respective procedure and instruments utilised for the analysis of physicochemical properties

Physicochemical properties	Procedure/Instrument	Reference
Moisture	Dean and Stark's apparatus	(Ranganna, 1986)
Fat	Soxhlet apparatus	AOAC 960.39
Nitrogen and protein (N × 6.25)	Kjeldahl unit [Pelican Kelplus-Classic DX VATS (P)]	AOAC 920.152
CHO	Difference method	(Cheng <i>et al.</i> , 2021)
Fibre	Crude fibre was determined by dilute acid and alkali hydrolysis	(Dhingra <i>et al.</i> , 2012)
Ash content	Combustion method	AOAC 940.26

incubator operating at 200 rotations per minute for 3 h. After centrifugation, the mixture was filtered through Whatman grade 41 filter paper to isolate the supernatant. A digital pH meter (model: 153-S), M/S Hitech Association, Delhi, was used to estimate the pH.

### 2.2.3. Colour

The colour of the seeds sample was estimated by measuring the  $L^*$   $a^*$   $b^*$  values of the seed samples using a handheld chromameter (Konica Minolta CR-400). The  $L^*$  value ranges from 0 (black) to 100 (white) and measures lightness. The  $a^*$  and  $b^*$  values in this system range from -100 (greenness) to +100 (redness) and from -100 (blueness) to +100 (yellowness), respectively. After determining the physicochemical properties, the seeds at varied moisture levels were estimated for their physical, engineering, and thermal properties.

## 2.3. Physical properties of fennel seeds

### 2.3.1. Geometrical dimensional properties

A digital vernier calliper (Electronic digital calliper, China) with a least count of 0.01 mm was used to measure the length ( $L$ ), width ( $W$ ), and height ( $H$ ), where 25 fennel seeds were chosen randomly in order to estimate their physical parameters. The measurements of  $L$ ,  $W$ , and  $T$  were recorded in millimetres.

### 2.3.2. Geometric mean diameter

The geometric mean diameter ( $G_{md}$ ) provides insight into the overall shape of a seed. To determine the  $G_{md}$  of the fennel seeds at different moisture levels, Eq. (2) was employed (Mohsenin, 1986):

$$G_{md} = \{LWT\}^{1/3}, \quad (2)$$

here:  $G_{md}$  – the geometric mean diameter (mm), whereas  $L$ ,  $W$ , and  $T$  – length, width, and thickness of the seeds, respectively (mm).

### 2.3.3. Sphericity

Sphericity quantifies the extent to which a product exhibits a spherical shape and is a measure of the compactness of the material. It is determined by comparing the surface area of a sphere having the same volume as the object to the total surface area of the object itself, offering a measure of how closely the object's surface resembles that of a sphere. Sphericity was determined using Eq. (3) (Vishwakarma *et al.*, 2015):

$$\Psi = \frac{LWT^{1/3}}{L}, \quad (3)$$

$\Psi$  – sphericity (%).

### 2.3.4. Seed surface area

The surface area is a representation of the total combined area of all the individual surfaces that comprise an object, and it is typically expressed in  $\text{mm}^2$ :

$$Sa = \pi G_{md}^2, \quad (4)$$

$Sa$  – seed surface area ( $\text{mm}^2$ ), and  $G_{md}$  stands for the geometric mean diameter of the seeds (mm) (Aghajani *et al.*, 2012; Singh and Meghwal, 2020).

### 2.3.5. Seed volume

Seed volume ( $\text{mm}^3$ ) and denotes the total spatial extent occupied by the given amount of fennel seeds. Measurement of seed volume plays a crucial role in evaluating quality parameters and was calculated using Eq. (5) (Bajpai *et al.*, 2020):

$$V = \frac{\pi B^2 L^2}{6(2L - B)}, \quad (5)$$

where:  $B$  – ( $WT$ ) 0.5,  $W$  – width and  $T$  – thickness (mm),  $V$  – seed volume ( $\text{mm}^3$ ), and  $L$  is length (mm).

### 2.3.6. Thousand seed mass ( $M_{1000}$ )

The mass of a randomly selected sample of 1000 seeds was determined using a precision electronic balance (Sartorius BSA224S-CW, Germany) having a least count of 0.0001 g.

## 2.4. Gravimetric characterisation

### 2.4.1. Bulk density, true density, and porosity

The bulk density of fennel seeds was determined by dividing the weight of the seeds by the space they occupy or the volume of the fennel seeds and was expressed in  $\text{kg m}^{-3}$ . True density of fennel seeds was measured using the liquid displacement method. This process entailed measuring the seed mass and immersing it in a measuring cylinder containing toluene. The amount of toluene displaced during this step was carefully noted, enabling the calculation of the true density, which was likewise expressed in  $\text{kg m}^{-3}$  (Kumar *et al.*, 2023).

Porosity quantifies the unoccupied spaces within the seeds, also known as voids, using Eq. (6) (Aviara *et al.*, 2013):

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} 100, \quad (6)$$

where:  $\varepsilon$  means porosity (%),  $\rho_t$  is true density ( $\text{kg m}^{-3}$ ), and  $\rho_b$  is bulk density ( $\text{kg m}^{-3}$ ).

## 2.5. Flow and frictional properties

### 2.5.1. Angle of repose

To ascertain the angle of repose, a hollow cylinder with dimensions of 4.7 cm in height and 5.5 cm in diameter was used. This cylinder was placed on a circular plate and filled with fennel seeds until reaching the brim.

Afterwards, the cylinder was gently removed, allowing the fennel seeds to settle naturally into a conical shape on the plate. Measurements of the resulting cone, including both its diameter and height, were documented (Mirzabe *et al.*, 2021):

$$\theta = \tan^{-1}(2h/d), \quad (7)$$

where:  $\theta$  is the angle of repose ( $^{\circ}$ ),  $h$  is the cone height (mm), and  $d$  is the cone diameter (mm).

### 2.5.2. Static coefficient of friction

The coefficient of friction measures resistance between a surface and granular materials. To determine the coefficient of the fennel seeds, five diverse surfaces were selected: steel, aluminium, plywood, cardboard, and glass sheets. A hollow box without a cover was filled with fennel seeds and positioned on the designated surface. Subsequently, the box was lifted carefully, and the surface was gradually tilted until the fennel seeds commenced their downward slide. The angle of tilt and coefficient of friction for the different surfaces were noted carefully:

$$\mu = \tan \alpha, \quad (8)$$

where:  $\mu$  is the static coefficient of friction and  $\alpha$  is the angle at which the seeds slid from the surface.

## 2.6. Drag properties

Drag properties, including the drag coefficient ( $C_d$ ), terminal velocity, and projected area, are essential to understand the interaction of the particles with a fluid medium, which is dependent on various variables, including the shape, surface roughness of the particles, and flow conditions; the drag coefficient measures the resistance that an object encounters when passing through a fluid.

### 2.6.1. Terminal velocity

This parameter is widely studied in relation to the physical properties of seeds (Gojiya *et al.*, 2023; Sudha *et al.*, 2024). The terminal velocities were measured using self-constructed apparatus designed for small grains employing the suspension method. The primary components of this apparatus were a digital hot wire anemometer (Lutron AM-4204HA), wire screens to hold fennel seeds, an electric blower with a speed-adjustable rotation, and pipes made of PVC and transparent plastic for the airflow channel. In every measurement, 1000 seeds at varied moisture level for each moisture content value were dropped in the plastic pipe and held back by a wire filter. The fennel seed sample was subsequently lifted within the transparent plastic pipe by using the air that flowed upward in the pipe from the bottom once the blower was turned on. The blower's spinning speed was changed to cause the samples to float steadily at a specific level. A hot wire anemometer was used to measure the air flow speed at that level, which was equal

to the terminal velocity of the fennel seed sample under these conditions. There were three radial locations in the plastic pipe where measurements were taken: the centre, the left, and the right. The final terminal velocity of the fennel seeds under test was determined by averaging the values. For every moisture content value, three replications of each variety of the fennel seeds were made.

### 2.6.2. Drag coefficient

A dimensionless quantity that measures an object's drag or resistance in a fluid environment, such as air or water, is the drag coefficient, or  $C_d$ . Additionally, determining an object's terminal velocity enables the computation of its drag coefficient:

$$C_d = \frac{2mg}{\rho_f A v_{\infty}^2}. \quad (9)$$

### 2.6.3. Projected area

A digital camera positioned perpendicular to the seed surface was used to take high-resolution pictures in order to calculate the projected area of each fennel seed. Consistent lighting and little shadow interference were guaranteed by the camera configuration. To improve image clarity and allow accurate border recognition, each seed was positioned against a contrasting background.

ImageJ software, an open-source image analysis tool, was used to import the collected images. Calibration of the picture using a recognized reference scale that was positioned within the frame for the accuracy of the measurement is represented in Fig. 2. Based on the calibration scale, this region was converted from pixels to square millimetres.

## 2.7. Thermal aspects of fennel seeds

TPS 500 was used to measure specific heat, thermal conductivity, and thermal diffusivity of the fennel seeds. For determination of the thermal properties, 10 g of seeds at varied moisture content, *i.e.*, 10, 14, 18, and 22%, were used and placed on a hot disc plate. The values for the specific heat, thermal conductivity, and diffusivity were obtained simultaneously using the Kapton 5601 chip. Specific heat is

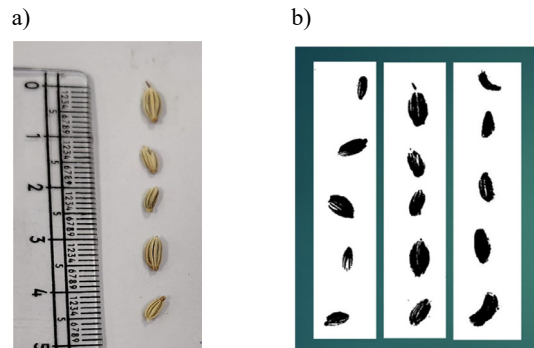


Fig. 2. Fennel seeds: a) captured, b) obtained through digital imaging.

the measure of heat energy needed to increase the temperature of a given mass of a substance by one degree Celsius or one Kelvin. In contrast, thermal conductivity, which indicates a material's ability to conduct heat, is a property that specifies how effectively a substance can transmit heat. High thermal conductivity materials excel at effectively transmitting heat, whilst low thermal conductivity materials do not transmit heat as effectively. Thermal diffusivity measures how quickly heat may diffuse or spread across a medium. It considers the material's density and specific heat capacity, as well as its thermal conductivity and capacity to conduct heat. It essentially measures how quickly a material can respond to temperature changes.

### 2.8. Statistical analysis

The mean values obtained in the physicochemical analysis were compared using the Duncan test. The different properties of the fennel seeds were tested at varied moisture levels, specifically from 10 to 22%. Each test was performed in triplicates, and the mean  $\pm$  SD values were estimated, followed by the variance estimation using two-way ANOVA at a 5% significance level. Linear regression analysis was also done to obtain the regression equation and coefficient of determination ( $R^2$ ) for all parameters. This helped to understand the linear relationship between the dependent and independent variables and identify the relationship between the variables.

## 3. RESULTS AND DISCUSSION

The ANOVA results from the statistical analysis for the three fennel seed varieties are presented in Table 2.

### 3.1. Proximate composition

The proximate composition of the three varieties of fennel seeds is represented in Table 2. The moisture content for the three varieties of the fennel seeds AF-1, AF-2, and AF-3, was found to be  $10.33 \pm 0.58\%$ ,  $10.5 \pm 0.50\%$ , and  $10.16 \pm 0.29\%$ , respectively. Moisture content is subject to variations based on humidity, temperature, the timing of harvest, prevailing climate, and the storage conditions employed. The amount of carbohydrates was found to be the highest compared to the other proximate parameters. The fennel seeds were rich in fibre, which accounted for  $21.53 \pm 1.76\%$ ,  $21.23 \pm 2.05\%$ , and  $13.36 \pm 4.12\%$  in the AF-1, AF-2, and AF-3 varieties, respectively, with AF-3 having the lowest fibre content. From this perspective, AF-1 and AF-2 are more valuable for the digestive process because the fibre content is very important in this aspect. The lowest fat content was determined in the AF-2 variety, which was equivalent to  $10.42 \pm 0.71\%$ , showing lower palatability compared with AF-1 and AF-3; in addition, the lower the fat content, the higher the moisture content (AF-2).

**Table 2.** Percentage content (mean  $\pm$  standard deviation) of the proximate values of fennel seeds

Proximate parameter	Variety	Percentage content (mean $\pm$ SD)
Moisture	AF-1	10.33 $\pm$ 0.58a
	AF-2	10.50 $\pm$ 0.50a
	AF-3	10.17 $\pm$ 0.29a
Carbohydrate	AF-1	33.05 $\pm$ 3.70a
	AF-2	33.50 $\pm$ 3.14a
	AF-3	38.71 $\pm$ 5.12a
Protein	AF-1	13.43 $\pm$ 2.26a
	AF-2	15.69 $\pm$ 0.49a
	AF-3	15.41 $\pm$ 1.32a
Ash	AF-1	7.65 $\pm$ 0.31a
	AF-2	8.67 $\pm$ 0.35b
	AF-3	8.22 $\pm$ 0.24ab
Nitrogen	AF-1	2.14 $\pm$ 0.36a
	AF-2	2.54 $\pm$ 0.02a
	AF-3	2.46 $\pm$ 0.21a
Crude Fibre	AF-1	21.53 $\pm$ 1.76b
	AF-2	21.23 $\pm$ 2.05b
	AF-3	13.36 $\pm$ 4.12a
Fat	AF-1	14.00 $\pm$ 1.10b
	AF-2	10.42 $\pm$ 0.71a
	AF-3	13.96 $\pm$ 1.39b

Different letters represent significant differences at  $p < 0.05$ . Groups sharing the same letter are not significantly different ( $p > 0.05$ ).

The highest ash content was observed in the AF-2 variety, equivalent to  $8.67 \pm 0.35\%$ ; this was due to the highest mineral content. The highest protein level was found in the AF-2 variety, which was equivalent to  $15.69 \pm 0.49\%$ . The crude nitrogen content was found to have the highest value for the AF-2 variety. (Noreen *et al.*, 2023) conducted a study on fennel seeds and reported the following contents: moisture  $7.83 \pm 0.02\%$ , protein  $11.86 \pm 0.01\%$ , fat  $10.31 \pm 0.02\%$ , fibre  $19.14 \pm 0.01\%$ , and ash  $11.39 \pm 0.02\%$  in fennel seeds. (Saber and Eshra, 2019) conducted proximate analysis of fennel seeds and found the contents of moisture, crude protein, crude fat, crude fibre, and ash of 8.04, 10.18, 10.71, 18.01, and 12.87%, respectively, and the carbohydrate content was found to be 40.19%. The USDA proximate values for the protein, lipid, ash, carbohydrates,

and total dietary fibre content in fennel seeds were found to be 15.8, 14.9, 8.22, 52.3, and 39.8 g, respectively. The Duncan test revealed significant differences in the mean values of the ash, crude fibre, and fat contents among the three different varieties of the fennel seeds.

### 3.2. pH and colour

The pH values for the three different varieties of the fennel seeds were found to be  $5.84 \pm 0.03$ ,  $5.9 \pm 0.02$ , and  $5.97 \pm 0.02$ , respectively, suggesting their slightly acidic nature. The  $L^*$  values for the AF1, AF2, and AF 3 fennel seeds were 59.02, 61.13, and 57.21, whereas the  $a^*$  values were 1.12, -0.05, and 2.97, respectively. The  $b^*$  values were 23.69, 22.09, and 21.26 for the AF-1, AF-2, and AF-3 seeds. The  $L^*$  value, which ranges from 0 (black) to 100 (white), is a measure of the lightness of the colour of a sample. The  $a^*$  and  $b^*$  values range from -100 (greenness) to +100 (redness) and from -100 (blueness) to +100 (yellowness), respectively. The  $L^*$  values were higher for the AF2 variety of the seeds, indicating that it was lighter in colour than the other varieties of the seeds. The AF2 variety had the lowest  $a^*$  values; hence, it can be estimated that the seeds are greener than the other varieties. The AF1 variety had the highest  $b^*$  values; hence, it can be interpreted that these seeds have a greater degree of yellowness than the other varieties. The Duncan test revealed significant differences in the mean values of pH,  $L^*$ , and  $a^*$  among the three fennel seed varieties, as presented in Table 3.

### 3.3. Geometrical dimensions

The design of different processing units for the development of different sorting and separating units is greatly affected by the dimensional qualities of the seeds, particularly their size and form. Furthermore, it is also required for the development of various sorting and separating mechanisms. This includes the design of sieves and various screens used in sorting units. It may also be required for the development of various air separators, gravity separators, and optical sorting machines (Berlage *et al.*, 1989; Larsen and Andreasen, 2004).

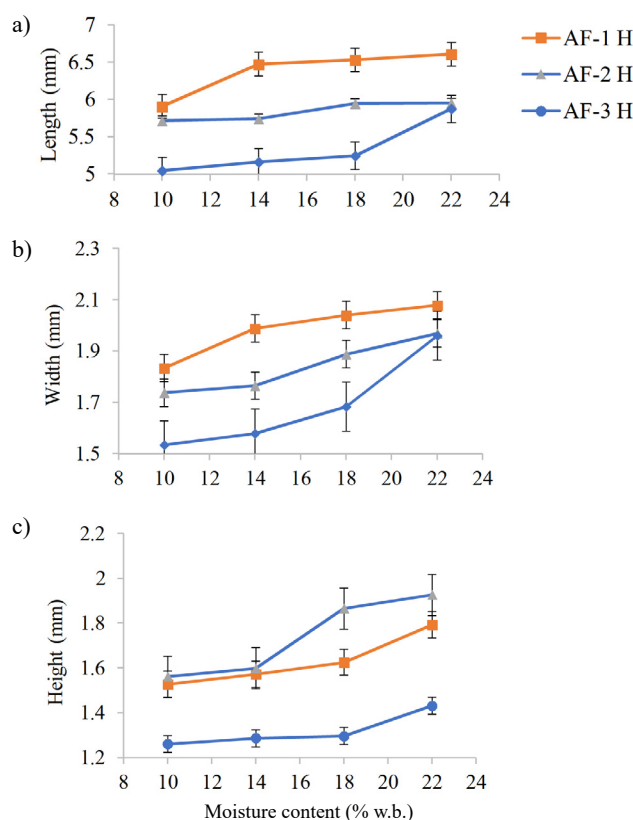
**Table 3.** pH and colour values ( $L^*$ ,  $a^*$  and  $b^*$ ), mean  $\pm$  standard deviation for the three varieties of fennel seeds

Parameter	Mean $\pm$ SD		
	AF1	AF2	AF3
pH	$5.84 \pm 0.03a$	$5.90 \pm 0.02b$	$5.97 \pm 0.02c$
$L^*$	$59.02 \pm 1.16a$	$61.13 \pm 0.64b$	$57.21 \pm 0.05a$
$a^*$	$1.12 \pm 0.59b$	$-0.053 \pm 0.012a$	$2.97 \pm 0.41c$
$b^*$	$23.69 \pm 1.44a$	$22.09 \pm 0.95a$	$21.26 \pm 1.86a$

Different letters represent significant differences at  $p < 0.05$ . Groups sharing the same letter are not significantly different ( $p > 0.05$ ).

### 3.4. Seed shape, size, and thickness

The length of the fennel seeds increased significantly ( $p < 0.05$ ) with the moisture content. It was found to increase significantly from 5.91 to 6.61 mm for the AF-1 variety, from 5.71 to 5.95 mm for the AF-2 variety, and from 5.04 to 5.87 mm for the AF-3 variety. The maximum increase in the length of the fennel seeds was found in the AF-3 variety of seeds. The cellular arrangement of seeds and penetration of water into the cell system may further increase the turgor pressure inside the cell, causing an increase in the size of the cells; this could be responsible for the increased expansion in the AF-3 variety of the seeds. The width of the fennel seeds increased from: 1.98 to 2.08, 1.73 to 1.96, and from 1.53 to 1.96 mm for the AF-1, AF-2, and AF-3 varieties of seeds, respectively. A significant increase in the thickness was observed for the three varieties of fennel seeds, ranging from 1.53 to 1.79 mm, respectively. The linear increment in the length, width, and height is shown in Fig. 3. The increase in the dimensional properties with an increase in the moisture content has been found in various seeds, including fluted pumpkin seeds (Igbozulike and Amamgbo, 2019), barley (Sologubik *et al.*, 2013), quinoa seeds (Jan *et al.*, 2019) Chiroji seeds (Kumar *et al.*, 2016), and fenugreek seeds (Meghwal and Goswami, 2012). The



**Fig. 3.** Relationship between: a) length, b) width, and c) height and moisture content.

**Table 4.** Linear regression equations with coefficient of determination ( $R^2$ ) for the length, width and height for varietal fennel seeds;  $m^*$  represents the moisture content in the linear regression equation

Dimensional properties	AF-1		AF-2		AF-3	
	Linear regression equation	Coefficient of determination	Linear regression equation	Coefficient of determination	Linear regression equation	Coefficient of determination
Length (L)	$0.05m^* + 5.52$	0.76	$0.02m^* + 5.47$	0.85	$0.06m^* + 4.30$	0.80
Width (W)	$0.02m^* + 1.67$	0.89	$0.02m^* + 1.51$	0.95	$0.03m^* + 1.13$	0.87
Thickness (T)	$0.02m^* + 1.29$	0.89	$0.03m^* + 1.19$	0.91	$0.01m^* + 1.11$	0.77

regression equation and coefficient of determination show a linear increase in the fennel seed length, width, and thickness, as depicted in Table 4.

### 3.5. Geometric mean diameter

The geometric mean diameter for the three varieties of the fennel seeds ranged from: 2.52 to 2.87, 2.48 to 2.79, and from 2.13 to 2.53 mm for the AF-1, AF-2, and AF-3 seed varieties, respectively. The regression equations represent the linear increase in the geometric mean diameter of the three varieties of the fennel seeds. The linear increase was significant ( $p < 0.05$ ) at the 5% level, with an increase in the moisture for the three varieties of the fennel seeds, as shown in Fig. 4. The regression equation representing the linear increase in the geometric mean diameter is shown in Eqs (10)-(12):

$$G_{mdAF-1} = 0.0282 m^* + 2.266 \quad (R^2 = 0.94), \quad (10)$$

$$G_{mdAF-1} = 0.029m^* + 2.1594 \quad (R^2 = 0.89), \quad (11)$$

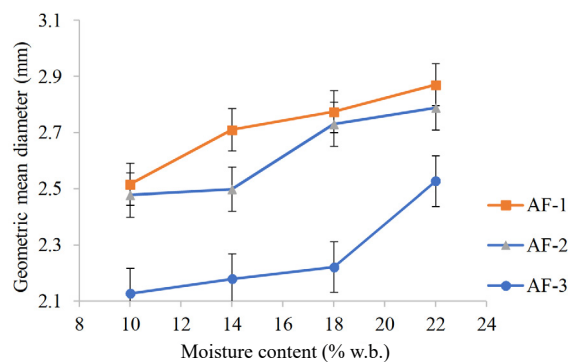
$$G_{mdAF-2} = 0.0311m^* + 1.7658 \quad (R^2 = 0.79), \quad (12)$$

$G_{md}$  – geometric mean diameter,  $m^*$  represents the moisture content in the linear regression equation.

Increased moisture content leads to water absorption by seeds, resulting in internal swelling and physical expansion. This process ultimately results in an increased geometric mean diameter.

### 3.6. Sphericity

The sphericity of the three varieties of the fennel seeds increased with the increase in the moisture content from 0.43 to 0.44 and from 0.43 to 0.47% for the AF-2 and AF-3 seed varieties, respectively, whereas for the AF-1 variety, sphericity first decreased at 14% moisture followed by an increase at 18%. However, a non-significant difference in sphericity was found for the different fennel seed varieties with varied moisture content ( $p > 0.05$ ). The increase in the sphericity of the seeds suggests that, with an increase in the moisture content, the AF-2 and AF-3 fennel seeds became more spherical. However, for the AF-1 variety, the intercellular arrangement could have decreased the sphericity

**Fig. 4.** Relationship between geometric mean diameter and moisture content.

ricity at an initial moisture increase, followed by a further increase in sphericity as the moisture content increased. At low moisture levels, the length, width, or thickness may expand more rapidly than the others. This differential expansion can temporarily reduce the object's sphericity, making it appear less spherical due to anisotropic expansion. As moisture increases further, the remaining dimensions catch up, making the shape rounder and increasing sphericity. Reduction in the sphericity of the seeds with an increase in moisture has been seen in pigeon peas. An increase in sphericity was also found in various seeds, including kenaf seeds (Izli, 2015) and soybean seeds (Alibas and Koksall, 2015). The linear increment is represented in Fig. 5, and the linear regression equations are represented by Eqs (13)-(15):

$$\Psi_{AF-1} = 0.0005m^{*2} - 0.0136m^* + 0.5147 \quad (R^2 = 0.40), \quad (13)$$

$$\Psi_{AF-2} = 0.0035m^* + 0.394 \quad (R^2 = 0.98) \quad (14)$$

$$\Psi_{AF-3} = 0.0011m^* + 0.4086 \quad (R^2 = 0.88), \quad (15)$$

$m^*$  represents the moisture content in the linear regression equation.

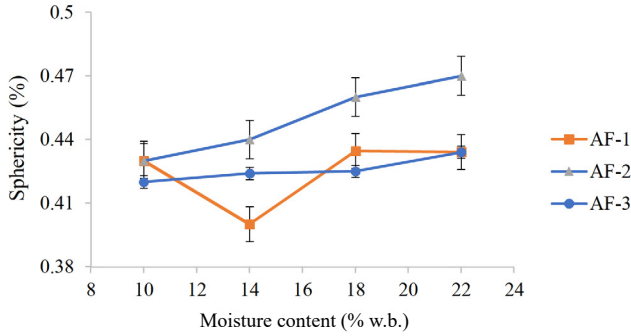


Fig. 5. Relationship between sphericity and moisture content.

3.7. Seed surface area and seed volume

The seed surface area of the three fennel varieties increased significantly ( $p < 0.05$ ) with an increased moisture content from 10 to 22%. The fennel seed surface area increased from 20.02 to 26.02 mm<sup>2</sup> for AF-1, from 19.50 to 24.73 mm<sup>2</sup> for AF-2, and from 14.41 to 20.33 mm<sup>2</sup> for the AF-3 variety. Linear increases in all three varieties were observed, as depicted in Eqs (16)-(18):

$$Sa_{AF-1} = 0.4989m^* + 15.303 \quad (R^2 = 0.9997), \quad (16)$$

$$Sa_{AF-2} = 0.4872m^* + 14.202 \quad (R^2 = 0.9066), \quad (17)$$

$$Sa_{AF-3} = 0.4628m^* + 8.9685 \quad (R^2 = 0.7864), \quad (18)$$

$Sa$  – seed surface area,  $m^*$  represents the moisture content in the linear regression equation.

A similar increase in the seed surface area was seen in jamun seeds (Bajpai *et al.*, 2020), barley seeds (Aghajani *et al.*, 2012), and aged pea seeds (Mahawar *et al.*, 2018). The volume of the seeds increased from: 6.21 to 7.58, 4.83 to 7.10, and from 3.50 to 5.16 mm<sup>3</sup> for the AF-1, AF-2, and AF-3 varieties of seeds, respectively, with an increase in the seed moisture content. The linear increase in the volume of the seeds is depicted in Eqs (19)-(21), respectively:

$$Sv_{AF-1} = 0.1937m^* + 3.2625 \quad (R^2 = 0.9658), \quad (19)$$

$$Sv_{AF-2} = 0.2085m^* + 2.594 \quad (R^2 = 0.927), \quad (20)$$

$$Sv_{AF-3} = 0.1663m^* + 1.0725 \quad (R^2 = 0.7807), \quad (21)$$

$Sv$  – seed volume,  $m^*$  represents the moisture content in the linear regression equation.

The linear relationship of seed volume and seed surface area is shown in Fig. 6. The same trend was seen in the case of bitter guard seeds (Ünal *et al.*, 2013), locust bean seeds (Sobukola and Onwuka, 2011), and sesame seeds (Darvishi, 2012). The surface area and volume of seeds increase with increasing moisture content due to a phe-

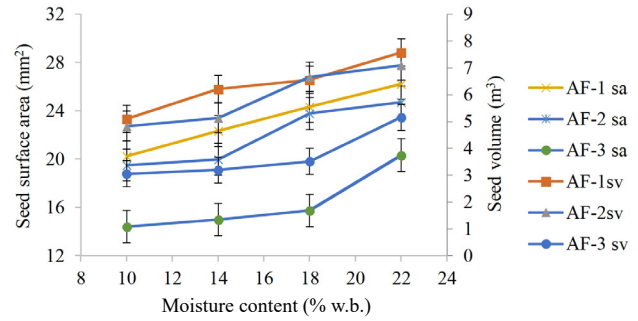


Fig. 6. Relationship between seed surface area ( $Sa$ ), seed volume ( $Sv$ ) and moisture content.

nomenon known as imbibition. During this process, seeds absorb water, leading to the swelling of their cellular structures, including starch and proteins. This swelling increases the seed’s dimensions, particularly length, width, and thickness, which results in an increase in the seed surface area and seed volume.

3.8. Thousand seed mass ( $M_{1000}$ )

An increase in moisture content resulted in a measurable rise in thousand-seed mass for all three fennel varieties, indicating a direct relationship between water absorption and seed weight. The linear increase in the thousand seed mass ( $M_{1000}$ ) of the seeds is depicted in Eqs (22)-(24), respectively:

$$M_{1000AF-1} = 17.017m^* + 4.8989 \quad (R^2 = 0.98), \quad (22)$$

$$M_{1000AF-2} = 10.5m^* + 5.7033 \quad (R^2 = 0.84), \quad (23)$$

$$M_{1000AF-3} = 15.333m^* + 4.9467 \quad (R^2 = 0.90), \quad (24)$$

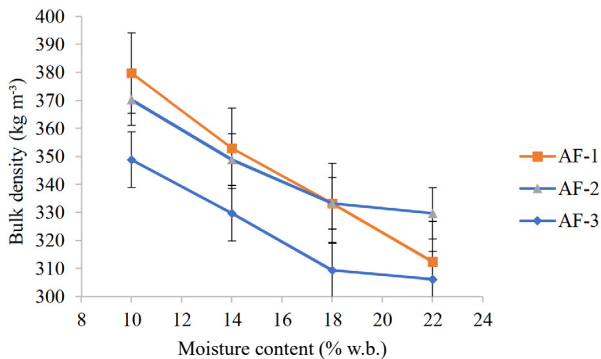
$m^*$  represents the moisture content in the linear regression equation.

Due to the hygroscopic nature of seeds, the mass of thousand seeds increases as the moisture content rises. Seeds gain weight when they collect moisture from their surroundings through the attachment of the water molecules to their internal and external structures. The moisture could get trapped in the cell walls and vacuoles of seeds due to their cellular structure. Higher moisture content causes swelling of the cells, which increases the overall mass of fennel seeds, resulting in a significant alteration in their density.

3.9. Gravimetric properties

3.9.1. Bulk density, true density, and porosity

Gravimetric properties play an essential role in various food processes, including the drying and aeration process, which is also related to the heat and mass transfer of moisture. These properties are further helpful in the design of



**Fig. 7.** Relationship between bulk density and moisture content.

various hoppers and storage containers. The bulk density of the fennel seeds of three varieties decreased significantly ( $p < 0.05$ ) from: 379.867 to 312.5, 370.37 to 329.75, and from 348.93 to 306.19  $\text{kg m}^{-3}$  with an increase in the moisture from 10 to 22%. The linear increase in the bulk density is represented in Fig. 7. The linear shape and size of the seeds increased with an increase in their moisture content, which caused adsorption of the moisture by the seeds. The volume of the seeds could have relatively increased more when compared to their overall mass, causing a decrease in the bulk density of the three varieties of the fennel seeds. The linear relationship the between bulk density and moisture content of the seeds is represented in Eqs (25)-(27):

$$Bd = -5.5451m^* + 433.41 \quad (R^2=0.995), \quad (25)$$

$$Bd = -3.4366m^* + 400.58 \quad (R^2 = 0.9205), \quad (26)$$

$$Bd = -3.7161m^* + 383.01 \quad (R^2 = 0.9315), \quad (27)$$

$Bd$  – bulk density,  $m^*$  represents the moisture content in the linear regression equation.

A similar trend was also seen for various seeds like chickpea seeds and locust bean seeds (Sobukola and Onwuka, 2011). The drop in bulk density is due to the fact that, during the moisture absorption phase, the air molecules in the seed occupy more space than the absorbed moisture, rendering the seed less dense. The highest bulk density was found for the AF-1 variety of the seeds, which suggests that the expansion and increase in the volume of the seeds was lesser for the AF-1 variety compared to the other varieties.

True density is determined by considering the mass of seeds while disregarding any empty spaces or pores within them. Pre-existing knowledge and comprehension of true density are beneficial for developing a process of seed separation from other impurities that are either heavier or lighter. True density decreased from 1000 to 666.66  $\text{kg m}^{-3}$  for all three varieties of the fennel seeds. However, the difference was insignificant ( $p < 0.05$ ) for all three varieties. Figure 8 represents the linear decrease in the true density

with increased moisture content. The decrease in the true density may have occurred due to an increase in the volume of the seeds with increased moisture adsorption in relation to the mass of the seeds. The linear relationship between true density and moisture content is shown in the Eqs (28)-(30):

$$\rho_t \text{ AF-1} = -33.333m^* + 1366.7 \quad (R^2 = 0.8), \quad (28)$$

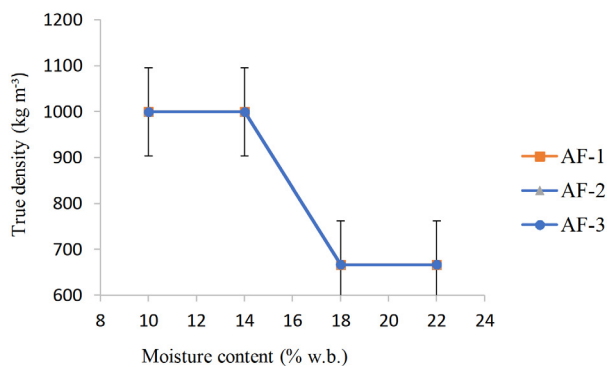
$$\rho_t \text{ AF-2} = -33.333m^* + 1366.7 \quad (R^2 = 0.8), \quad (29)$$

$$\rho_t \text{ AF-3} = -33.333m^* + 1366.7 \quad (R^2 = 0.8), \quad (30)$$

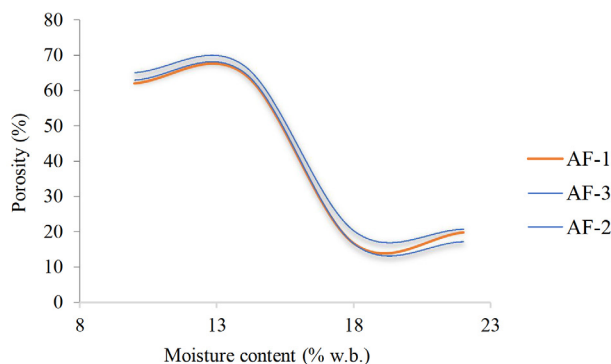
$\rho_t$  – true density,  $m^*$  represents the moisture content in the linear regression equation.

The decreasing trend of true density with increasing moisture content has also been observed in locust beans (Sobukola and Onwuka, 2011), rapeseed (Izli *et al.*, 2009), and jamun seeds (Bajpai *et al.*, 2020). The porosity of fennel seeds was found to increase at 14%, then decrease at 18%, followed by a sudden increase at 22% with an increase in the moisture content from 10 to 22% for all three fennel seed varieties.

The porosity of the seeds was found to increase at 14%, followed by a decrease at 18%, and then again increased at 22% for the three seed varieties; this nonlinear decrease is represented in Fig. 9 and Eqs (31)-(33). The seed coat may initially enlarge as the moisture level rises, but it may later



**Fig. 8.** Relationship between true density and moisture content.



**Fig. 9.** Relationship between porosity and moisture content.

be compacted by overhydration. It is possible that this early swelling will momentarily reduce porosity. The densification of the seed coat, which closes off some of the seed's pores and gaps, may cause the compacting effect. Further moisture may eventually reach deeper seed layers or cause internal structures to absorb water. This extended moisture exposure may cause the seed to expand slowly, possibly creating additional holes or voids inside the seed structure, increasing porosity. Hence, the nonlinear relationship could have occurred with varying moisture content. The change in the porosity ( $\varepsilon$ ) for the three varieties of the fennel seeds was significant ( $p < 0.05$ ):

$$\varepsilon_{AF-1} = 0.0069m^{*2} - 4.5865m^{*} + 112.28 \quad (R^2 = 0.75), \quad (31)$$

$$\varepsilon_{AF-2} = -0.0242m^{*2} - 3.8697m^{*} + 109.07 \quad (R^2 = 0.78), \quad (32)$$

$$\varepsilon_{AF-3} = -0.0223m^{*2} - 0.7818m^{*} + 109.96 \quad (R^2 = 0.78). \quad (33)$$

A non-linear decrease in the porosity was also found in coriander seeds, and a linear decrease in porosity has been found in watermelon seeds (Koocheki *et al.*, 2006). In contrast, an increase in seed porosity has been observed in barley seeds (Aghajani *et al.*, 2012) and jamun seeds (Bajpai *et al.*, 2020).

### 3.10. Angle of repose

The angle of repose was found to increase significantly ( $p < 0.05$ ) with the increase in the moisture content from 10 to 22%. In industries, the angle of repose helps determine the shape of storage containers and conveyors. The angle of repose was found to increase linearly from 79.38 to 82.24° for the AF-1 variety, from 79.14 to 82.18° for the AF-2 variety, and from 79.82 to 81.88° for the AF-3 variety, as represented in Fig. 10. The aggregation of seeds with increased moisture increased the angle of repose for all three varieties. This occurs because moisture forms a thin water film on the seed surface, enhancing adhesion and friction among the seeds and increasing their tendency to aggregate. As a result, seeds resist rolling or sliding,

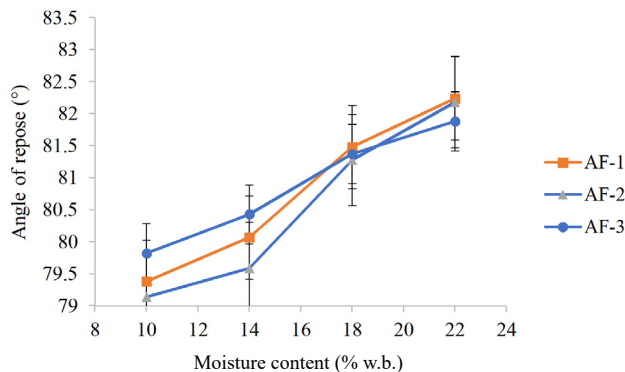


Fig. 10. Relationship between angle of repose and moisture content.

forming steeper piles, further increasing the angle of repose. The linear relationship between the angle of repose and the increase in moisture is represented in Eqs (34)-(36):

$$\theta_{AF-1} = 0.2497m^{*} + 76.797 \quad (R^2 = 0.9813), \quad (34)$$

$$\theta_{AF-2} = 0.2702m^{*} + 76.224 \quad (R^2 = 0.958), \quad (35)$$

$$\theta_{AF-3} = 0.1780m^{*} + 78.027 \quad (R^2 = 0.9878), \quad (36)$$

$\theta$  – angle of repose,  $m^{*}$  represents the moisture content in the linear regression equation.

The angle of repose was found to increase with the increase in moisture for various seeds like rapeseeds (Izli *et al.*, 2009), cumin seeds (Mollazade *et al.*, 2009), niger (Solomon and Zewdu, 2009), and barley (Aghajani *et al.*, 2012).

### 3.11. Coefficient of friction

The coefficient of friction for three varieties of fennel seeds was determined using different surfaces, including aluminium, wood, cardboard, and glass, at varied moisture levels in the range of 10-22%. The maximum coefficient of friction was found in the case of wood compared to the other surfaces. Friction is typically the highest on wooden surfaces due to the rough and porous nature of wood. This texture facilitates greater interlocking between surfaces and enables the absorption of moisture, thereby increasing grip. In contrast, surfaces such as steel and aluminium are smoother and less porous, resulting in reduced friction and allowing seeds to slide more easily. The coefficient of friction for the three fennel seed varieties was found to increase significantly ( $p < 0.05$ ) for all surfaces with increased moisture content, as represented in Fig. 11. The coefficient of friction increases with rising moisture content due to the presence of water on the seed surface, imparting slight

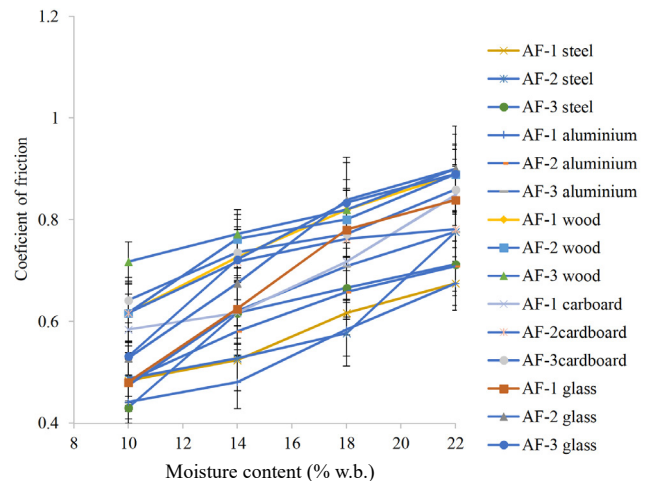


Fig. 11. Relationship between coefficient of friction and moisture content.

stickiness. This phenomenon enhances adhesion between the seeds and the contact surface, thereby diminishing smooth sliding and increasing resistance to motion. It is usually the highest on wooden surfaces because wood is rough and porous, allowing the surface to interlock with the seeds and absorb moisture, increasing grip. In contrast, surfaces like steel and aluminium are smoother and less porous; hence, seeds slide more easily with lower friction. The linear regression equations are represented in Table 5 for different surfaces for three varieties of seeds.

**3.12. Drag properties**

The mean and standard deviation values for drag properties with an increase in the moisture content are presented in Table 6.

**3.12.1. Terminal velocity**

The terminal velocity of the AF-1, AF-2, and AF-3 fennel seed varieties increased linearly with an increase in the moisture content ( $p < 0.05$ ) from: 0.77 to 1.18, 0.67 to 1.19, and from 0.80 to 1.36  $m\ s^{-1}$ , respectively. The AF-2 variety of the fennel seeds showed the biggest increase in the terminal velocity. The linear relationship between terminal velocity and moisture content is shown in Eqs (37)-(39):

**Table 5.** Linear regression equations with coefficient of determination ( $R^2$ ) for the coefficient of friction for varietal fennel seeds

AF-1	AF-2	AF-3
Linear regression equations with coefficient of determination		
Steel		
$0.0167m^*+0.3086$	$0.0229m^*+0.2261$	$0.0224m^*+0.2488$
$R^2 = 0.9793$	$R^2 = 0.8499$	$R^2 = 0.8746$
Aluminum		
$0.0201m^*+0.2245$	$0.0188m^*+0.3072$	$0.0249m^*+0.2465$
$R^2 = 0.971$	$R^2 = 0.9816$	$R^2 = 0.9681$
Wood		
$0.0228m^*+0.3987$	$0.0214m^*+0.4249$	$0.0149m^*+0.5649$
$R^2 = 0.9904$	$R^2 = 0.9465$	$R^2 = 0.9865$
Cardboard		
$0.0223m^*+0.3351$	$0.0135m^*+0.504$	$0.0172m^*+0.4765$
$R^2 = 0.9404$	$R^2 = 0.8941$	$R^2 = 0.9749$
Glass		
$0.0307m^*+0.1895$	$0.032m^*+0.2235$	$0.0296m^*+0.2701$
$R^2 = 0.9686$	$R^2 = 0.9696$	$R^2 = 0.9397$

$m^*$  represents the moisture content in the linear regression equation.

**Table 6.** Mean and standard deviation values for drag properties

AF-1			AF-2			AF-3								
			Moisture content (%)											
10	14	18	10	14	18	10	14	18						
Terminal velocity			6.49±0.01	0.86±0.001	0.88±0.004	1.18±0.003	6.53±0.01	0.81±0.016	1.009±0.003	1.19±0.003	6.27±0.013	0.89±0.03	1.16±0.01	1.36±0.00
Drag coefficient			0.45±0.002	0.64±0.003	0.68±0.002	1.01±0.01	0.39±0.006	0.602±0.037	0.71±0.006	0.95±0.007	0.59±0.002	0.69±0.08	0.96±0.04	1.37±0.003
Projected area			521±0.00	552±0.00	712.2±0.00	712.8±0.00	521±0.00	561±0.00	733±0.00	796±0.00	551±0.00	561±0.00	702.1±0.00	886.1±0.00

$$v_{\infty AF-1} = 3.33m^* + 0.4157 \quad (R^2 = 0.95), \quad (37)$$

$$v_{\infty AF-2} = 4.375m^* + 0.2236 \quad (R^2 = 0.99), \quad (38)$$

$$v_{\infty AF-3} = 4.8611m^* + 0.2778 \quad (R^2 = 0.96). \quad (39)$$

The increase in terminal velocity across moisture levels indicates that seed mass directly affects aerodynamic characteristics. The terminal velocity of the three varieties of fennel seeds differed significantly ( $p < 0.05$ ). Data analysis showed that seeds with the highest moisture content had the highest terminal velocity values, demonstrating a clear correlation between increased mass from water absorption and enhanced terminal velocity. Ghamari *et al.* (2014) found an increase in the terminal velocity of different varieties of chick pea seeds with an increase in the moisture content, where the Jam variety had the highest terminal velocity, which increased from 13.9 to 15.1  $m s^{-1}$  as the moisture content increased from 7.33 to 25%. (Basati *et al.*, 2019) also found an increase in the terminal velocity of lentil seeds from 6.75 to 7.39  $m s^{-1}$  as the moisture content increased from 8 to 24%. According to Stokes' Law, terminal velocity is achieved when the downward gravitational force is balanced by the upward drag force exerted by air resistance. The increase in the terminal velocity of fennel seeds with higher moisture content is primarily due to the physical and aerodynamic changes that occur as seeds absorb water. An increase in the moisture increases the downward gravitational force. The increased seed mass requires a higher air velocity to produce sufficient drag to balance the weight, resulting in an elevated terminal velocity (Obi, 2016).

### 3.12.2. Projected area

The projected area of the fennel seeds of the AF-1, AF-2, and AF-3 varieties increased with increasing moisture from: 521 to 712.8, 521 to 796, and from 551 to 886.1  $mm^2$ , respectively. Typically, fennel seeds are arranged by size and shape. The anticipated area is essential for effectively separating seeds from debris when constructing sorting equipment, such as air separators and vibrating screens. Sorting procedures may need to be modified for seeds with a higher projected area to ensure efficient separation. The linear relationship between projected area and moisture content is shown in Eqs (40)-(42). Kalkan and Kara (2011) found that the projected area of grains from different wheat cultivars, namely, cvs. Pehlivan, Kızıltan-91, Çeşit-1252, Bayraktar-2000, and Kırık grains increased linearly from: 15.51 to 20.81, 14.22 to 17.78, 14.84 to 19.79, 11.42 to 16.82, and from 11.78 to 16.95  $mm^2$  with increasing moisture content. A similarly positive linear relationship was found for Christmas Lima bean seeds (Aghkhani *et al.*, 2012):

$$y = 1839m^* + 330.26 \quad (R^2 = 0.8601), \quad (40)$$

$$y = 2866m^* + 216.49 \quad (R^2 = 0.892), \quad (41)$$

$$y = 2492.5m^* + 253.95 \quad (R^2 = 0.9424). \quad (42)$$

The linear increment in the projected area could be due to the fact that as the moisture content increased, the intercellular space of the fennel seeds expanded due to the absorption of moisture, causing enlargement of the seeds' dimensions, which resulted in an increase in the 2D surface of the seeds, subsequently increasing the projected area of the three varieties of the fennel seeds.

### 3.12.3. Drag coefficient

The drag coefficient is an important factor for characterizing the aerodynamic resistance of fennel seeds, which is essential for post-harvest procedures, including sorting and drying. The drag coefficient differed significantly among the three varieties of the fennel seeds ( $p < 0.05$ ). A linear correlation was found for the three varieties of the fennel seeds with the increase in the moisture content. The drag coefficient of the AF-1, AF-2, and AF-3 varieties of fennel seeds was in the range of 0.455-1.01, 0.38-0.95, and 0.58-1.37, respectively.

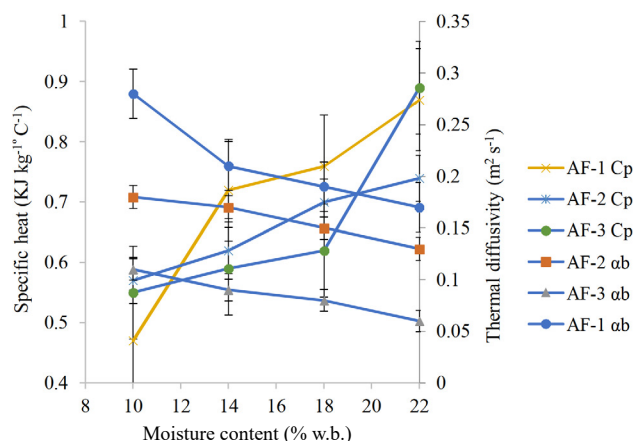
The drag coefficient changes with the seed mass, texture, aerodynamic characteristics, and varying moisture content, which is crucial for maximizing airflow and processing efficiency. Aerodynamic resistance, quantified by the drag coefficient, influences the behaviour of fennel seeds in airflow-based systems. This parameter determines the amount of airflow required to effectively suspend, separate, or move the seeds during post-harvest procedures such as drying, cleaning, and sorting. While lower aerodynamic resistance makes handling the seeds easier, higher resistance necessitates stronger airflow. By modifying airflow according to the drag coefficient, effective drying and sorting are guaranteed, energy consumption is reduced, and mechanical damage to the seeds is avoided. This knowledge is especially crucial since different moisture contents modify the aerodynamic resistance of seeds by affecting their weight and surface. The linear relationship between drag coefficient and moisture content is shown in Eqs (43)-(45):

$$y = 4.3293m^* + 0.0052 \quad R^2 = 0.9133, \quad (43)$$

$$y = 4.5395m^* - 0.0659 \quad R^2 = 0.9863, \quad (44)$$

$$y = 6.6005m^* - 0.1593 \quad R^2 = 0.9268. \quad (45)$$

Chavoshgoli *et al.* (2015) also found an increase in the drag coefficient of sunflower seeds from 0.59 to 0.95 for with an increase in moisture content. As the moisture content of the seed increases, it undergoes swelling, which

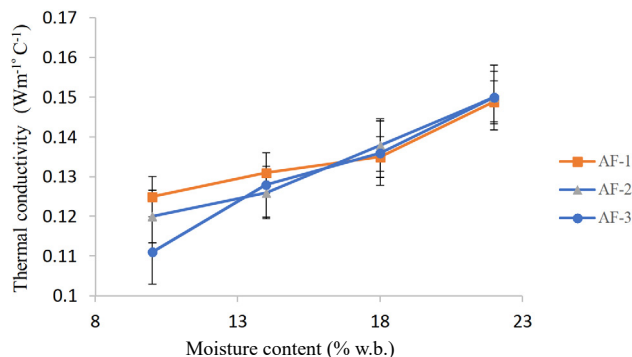


**Fig. 12.** Relationship of specific heat and thermal diffusivity with moisture content.

in turn enlarges its projected surface area. A larger surface area encounters heightened air resistance during movement, thereby increasing the drag experienced by the seed, further increasing the drag coefficient.

### 3.13. Thermal properties

Thermal properties help design various processing systems like cryogenic grinders, as they contribute to understanding the heat transfer in the samples. The three thermal properties which were studied are specific heat, thermal conductivity, and thermal diffusivity. The mean and the values of standard deviation are represented in Table 8. The specific heat was found to increase significantly ( $p < 0.05$ ) with the increase in the moisture content from: 0.47 to 0.87, 0.57 to 0.74, and from 0.55 to 0.89 MJ  $m^{-3}$  K. In contrast, thermal diffusivity decreased from 0.28 to 0.17, 0.30, 0.18 to 0.14, and from 0.11 to 0.06  $mm^2 s^{-1}$  for the three varieties of the fennel seeds. The thermal conductivity, however, increased from: 0.12 to 0.14, 0.12 to 0.15, and from 0.11 to 0.15  $W m^{-1} K$  for AF-1, AF-2, and AF-3,



**Fig. 13.** Relationship of thermal conductivity with moisture content.

respectively. The linear relationship of thermal properties is represented in Figs 12 and 13 and linear regression equations are represented in Table 7.

The increase in conductivity with an increase in moisture content could be attributed to higher water conductivity. As the moisture content rises, bulk density decreases, and diffusion is hindered, resulting in a decrease in thermal diffusivity. A similar trend for an increase in the specific heat was observed in pumpkin seeds (Kocabiyik *et al.*, 2009), red lentil seeds (Gharibzahedi *et al.*, 2014), rapeseeds (Izli *et al.*, 2009), and lentil seeds (Gharibzahedi *et al.*, 2014). The decreasing trend of thermal diffusivity was found in various seeds, including red lentil seeds (Gharibzahedi *et al.*, 2014) and roselle seeds (Bamgboye and Adejumo, 2010). Thermal diffusivity was found to be the lowest for the AF-3 fennel seeds, possibly due to their increased porosity. An increasing trend in the thermal conductivity was also observed in various seeds, including cumin seeds (Singh and Goswami, 2000), red lentil seeds (Gharibzahedi *et al.*, 2014), ajwain seeds (Singh and Meghwal, 2020), and roselle seeds (Bamgboye and Adejumo, 2010).

**Table 7.** Linear regression equation for thermal properties of the three seed varieties of fennel seeds as a function of moisture content

Thermal properties	Fennel seed varieties		
	AF-1	AF-2	AF-3
Specific heat $C_p$	$0.031m^* + 0.21$ $R^2 = 0.8877$	$0.0151m^* + 0.4172$ $R^2 = 0.9805$	$0.0264m^* + 0.2402$ $R^2 = 0.7805$
Thermal diffusivity $\alpha_b$	$-0.0087m^* + 0.3525$ $R^2 = 0.8909$	$-0.0043m^* + 0.2255$ $R^2 = 0.9797$	$-0.004m^* + 0.149$ $R^2 = 0.9846$
Thermal conductivity $k_b$	$0.0019m^* + 0.1046$ $R^2 = 0.9256$	$0.0026m^* + 0.0927$ $R^2 = 0.9797$	$0.0031m^* + 0.0813$ $R^2 = 0.983$

$m^*$  represents the moisture content in the linear regression equation.

**Table 8.** Statistical values for the three varieties of fennel seeds

Properties	Variables	F-ratio	p-value	F-critical
Length	Moisture	8.46	0.00a	2.64
	Fennel seed varieties	51.54	0.00b	3.03
Width	Moisture	10.34	0.00a	2.64
	Fennel seed varieties	18.08	0.00b	3.03
Thickness	Moisture	1.99	0.115ca	2.64
	Fennel seed varieties	6.57	0.002b	3.03
Geometric mean diameter	Moisture	18.79	0.000a	2.64
	Fennel seed varieties	61.66	0.000b	3.03
Sphericity	Moisture content	0.137	1.863ca	2.64
	Fennel seed varieties	0.030	3.552cb	3.035
Seed surface area	Moisture content	19.15	0.000a	2.64
	Fennel seed varieties	57.43	0.000b	3.03
Seed volume	Moisture content	17.62	0.000a	2.64
	Fennel seed varieties	47.74	0.000b	3.03
1000 seed mass	Moisture content	368.4	0.00b	3.01
	Fennel seed varieties	14.95	0.00a	3.40
Bulk density	Moisture content	149.4	0.000a	3.01
	Fennel seed varieties	62.89	0.000b	3.40
True density	Moisture content	0.994	0.412ca	3.01
	Fennel seed varieties	1.00	0.383cb	3.40
Porosity	Moisture content	158781	0.000a	3.01
	Fennel seed varieties	70.82	0.000b	3.40
Angle of repose	Moisture content	395.8	0.001a	3.01
	Fennel seed varieties	10.29	0.000b	3.40
Static coefficient of friction				
Steel	Moisture content	17.92	0.000a	3.01
	Fennel seed varieties	0.68	0.516cb	3.40
Aluminium	Moisture content	558.4	0.000a	3.01
	Fennel seed varieties	155.5	0.000b	3.40
Wood	Moisture content	221.1	0.000a	3.01
	Fennel seed varieties	13.01	0.000b	3.40
Cardboard	Moisture content	88.53	0.000a	3.01
	Fennel seed varieties	2.941	0.072cb	3.40
Glass	Moisture content	4383	0.000a	3.01
	Fennel seed varieties	258.2	0.000b	3.40
Drag properties				
Terminal velocity	Moisture content	59.76	0.00a	3.01
	Fennel seed varieties	9.801	0.00b	3.40
Drag coefficient	Moisture content	37.83	0.00a	3.01
	Fennel seed varieties	11.51	0.00b	3.40
Projected area	Moisture content	0.00	0.00ca	3.01
	Fennel seed varieties	0.00	0.00cb	3.40
Thermal properties				
Specific heat	Moisture content	7.11	0.00a	3.01
	Fennel seed varieties	0.009	0.99cb	3.40
Thermal diffusivity	Moisture content	7.39	0.00a	3.01
	Fennel seed varieties	48.99	0.00b	3.40
Thermal conductivity	Moisture content	17.6	0.00a	3.01
	Fennel seed varieties	0.342	0.71b	3.40

a – significance for different moisture contents at 5% level, b – significance for different ajwain seeds variety at 5% level, ca – no significance for different moisture contents at 5% level, cb – no significance for different fennel seeds variety at 5% level.

#### 4. CONCLUSIONS

The proximate analysis, pH, and colour values were estimated for the three fennel seed varieties, followed by the estimation of the physical and thermal properties of the three varieties by varying the moisture content for each variety from 10 to 22%. A significant difference between the means of ash, crude fibre, and fat content was found for AF-1, AF-2, and AF-3. The mean values of pH,  $L^*$ , and hue angle were significantly different for each variety of the fennel seeds. It was observed that the variation in the moisture content caused changes in the physical and thermal aspects of the fennel seeds. The dimensions of the seeds increased due to the entrapment of moisture in the cells. For the AF-1 variety, the sphericity decreased, followed by the increase in the moisture content. Seed surface area and seed volume increased significantly with the moisture content. A decrease in the bulk density and true density was observed with the increase in the moisture content. A non-linear decrease was observed in the porosity with the increase in the moisture content from 10 to 22%. The angle of repose increased for the three varieties of fennel seeds with the increase in the moisture content. The coefficient of friction increased with the increment in the moisture content; however, the increase was found to be higher in the case of wood when compared to the other selected surfaces. The analysis of the thermal properties suggested that, with the increase in the moisture content, specific heat increased, whereas thermal diffusivity was found to decrease. The AF-3 variety had the lowest thermal diffusivity because of the increased porosity of its seeds. To ensure optimal quality and customer satisfaction during processing, storage, and consumption, it is essential to understand the physical and thermal characteristics of fennel seeds. These characteristics play a crucial role in optimising processes. They support the development of equipment suited to the properties of fennel seeds, guaranteeing effective processing and storage. Furthermore, knowing the thermal characteristics helps the design of equipment for processes like drying, sterilising, and heating, ensuring these are carried out efficiently to preserve the quality of fennel seeds. Each variety showed specificity and can be chosen in food applications. Ultimately, this information is critical to producing better results and upholding the intended standards for preparing, storing, and consuming fennel seeds.

**Conflicts of Interest.** The authors declare no conflict of interest.

**Data Availability.** The data that support the findings of this study are available on request.

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