Evaluation of moisture dependent geometric and gravimetric properties of small-sized sesame and black caraway seeds using image analysis

Y. Y. Shallangwa\textsuperscript{a}, A. H. Alkali\textsuperscript{b}, and N. A. Aviara\textsuperscript{a}

\textsuperscript{a}Department of Agricultural and Environmental Resources Engineering, University of Maiduguri, Maiduguri, Nigeria; \textsuperscript{b}Department of Computer Engineering, University of Maiduguri, Maiduguri Nigeria

**ABSTRACT**

Sesame and black caraway seeds are important oil and medicinal grains that are small sized. The development of handling, processing, and storage facilities for the crops has been hampered by difficulties in measuring their geometric and gravimetric properties using Vernier caliper and micrometer screw gauge. Image analysis technique was chosen and applied in this study. Images of the seeds at different moisture levels were captured using a high resolution digital camera. The images in RGB were converted to Gray, then to Binary, and Noise was filtered, and the images subjected to threshold segmentation and analysis using LABVIEW software. Grain projected area and axial dimensions were determined. Volume was determined using liquid displacement. Dimensional analysis was used to select an appropriate grain shape as oblate spheroid. Calculated volume was obtained, and volume correction factor determined. One thousand grain mass was obtained using an electronic balance. Particle and bulk densities were determined using standard methods. Porosity was calculated using its relationship with particle and bulk densities. Results showed that as the moisture content of sesame and black caraway grains increased from 2.25% to 28.53% and 3.04% to 39.62%, respectively, the projected area, major and minor axes increased from 3.37 mm\(^2\) to 5.68 mm\(^2\), 0.3 mm to 0.452 mm and 0.287 mm to 0.45 mm (sesame), and from 1.041 mm\(^2\) to 5.136 mm\(^2\), 0.23 mm to 0.38 mm and 0.227 mm to 0.373 mm (caraway). In the above moisture ranges, volume and volume correction factor varied from 0.0214 mm\(^3\) to 0.0317 mm\(^3\) and 0.851 to 0.865 (sesame), and 0.01 mm\(^3\) to 0.0283 mm\(^3\) and 0.85 to 0.879 (caraway), respectively. W1000 increased from 2.9 to 3.875 g (sesame) and 2.644 to 3.78 g (caraway) while bulk and particle densities, and porosity decreased from 502.1 kg/m\(^3\) to 310.87 kg/m\(^3\), 828 kg/m\(^3\) to 378.4 kg/m\(^3\), and 39.4% to 17.85% for sesame, and from 560 kg/m\(^3\) to 269.8 kg/m\(^3\), 746.4 kg/m\(^3\) to 295.5 kg/m\(^3\), and 24.97% to 8.7% for caraway seed.

**Introduction**

Sesame (*Sesamum indicum* L.) (Figure 1) is an oilseed crop of the Pedaliaceae family. It is rich in oil, protein and carbohydrate with chemical analysis showing that it contains 57–63% oil, 23–25% protein, 20–25% carbohydrate, and 3–4% ash. The oil contains vitamins A, B, D and E, minerals and amino acids.\(^{[1,2]}\) The seeds vary in color depending on variety. Sesame is classified in the division Magnoliophyta, class Magnoliopsida, and order Scrophulariales, family Pedaliaceae. The largest producers of sesame seeds in 2007 were India, China, Myanmar, Sudan, Ethiopia, Uganda and Nigeria.\(^{[3]}\) The main varieties found in Nigeria are white and black or brown. Sesame is grown in many parts of the world...
on over 5 million acres.\textsuperscript{[4]} The crop is mainly cultivated in six Northern States of Nigeria (Bauchi, Plateau, Adamawa, Borno, Gombe, Taraba and Yobe States) and Abuja.\textsuperscript{[1,2]} The oil (known as teel oil) is used extensively for cooking, soap manufacture, food, and medicine. The plant is harvested when matured before it dries and piled on a platform or cemented surface or clean rock surface in V-shape and allowed to dry before it is shaken to allow the seeds to fall out of the pod.\textsuperscript{[5]}

Black caraway (\textit{nigella sativa}) (Figure 2) also known as Roman coriander, black cumin, meridian fennel and Persian cumin seed, is a member of the Ranunculaceae (buttercup) family.

The nutritional values of the seeds include provision of energy, fat, vitamins, minerals, and water. They have a pungent, anise-like flavor and are used as spices in bread, dessert liquors, casseroles, cuisine, cake, sauerkraut and other foods.

Caraway seeds are also used to add flavor to cheeses, such as bondost, pultost, havarti and Tilsit cheese. The oil is used to improve fragrance in soaps, lotions and perfume.\textsuperscript{[6]} Caraway is used as a breath freshener, and it has a long tradition of use in folk medicine. The seeds also function as analgesic, anti-bacterial, anti-inflammatory, anti-ulcer, anti-cholinergic, anti-fungal, anti-hypertensive, antioxidant, anti-spasmodic, antiviral, bronchodilator, gluconeogenesis Inhibitor, hepatoprotective, hypotensive, insulin sensitizing, interferon inducer, leukotriene antagonist, renoprotective and tumor necrosis factor alpha inhibitor agent.\textsuperscript{[7]}

\textbf{Figure 1.} Sesame seeds after threshing.

\textbf{Figure 2.} Black caraway seeds.
In Africa, the processing of crops is mainly carried out manually using traditional methods. The methods or operations may involve such operations as shelling, dehusking, winnowing, grinding, drying, frying, and cooking to mention a few. The manual methods are not only time-consuming but also wasteful, causing loss in quantity and quality of seeds and man-hour use. The above problems are also identifiable in the processing of sesame and black caraway grains.

In order to overcome these problems, there is a need to develop new systems for handling, processing and storing the two grains. The development of such systems and equipment, there requires knowledge of the engineering properties of the seeds. The properties could be physical consisting of the geometric, gravimetric and frictional properties or mechanical and thermal.

The use of conventional methods for obtaining the physical (geometric and gravimetric) properties of these seeds is quite difficult. The seeds are very small in size, making it almost impossible for them to be held in conventional equipments such as Vernier caliper, tracing paper, and micrometer screw gauge. There is, therefore, the need to apply new techniques to the determination of the geometric and gravimetric properties of such grains. One of these new techniques that can be applied is the image analysis technique. This technique was chosen for ease of application, simplicity and accuracy of results.

Image analysis is the extraction of meaningful information from images that are mainly digital, by means of image processing techniques. It refers to the extraction of numerical data from an acquired image. The color, size, shape, characteristics of plant products, and their capability to produce digital images suitable for further processing make modern image acquisition techniques highly adaptable tools in the study of these properties. Bio-morphological seed features may be analyzed by computer-aided image analysis systems and data quickly processed and stored in the hard disk, plotted or

Figure 3. Experimental set-up.
statistically elaborated. Image analysis tasks can be as simple as reading bar coded tags or as sophisticated as identifying a person from the face.

The technique allows the enhancement of images, as well as the identification and automatic isolation of particles for further study. It is a rapid and time-saving technique that allows for the acquisition of quantitative data that could be very difficult or even impossible to obtain otherwise. Recently, researches on the inspection of cereal kernels by image analysis, computer vision, or microscopic techniques have been reported. A large number of these studies used image analysis techniques for the classification and identification of cereal varieties or kernel quality.

Image analysis technique (machine vision system) is one of such systems that offer the prospect that researchers will be able to study seed surface features more closely and hence increase the available character set. Thus, it has potential use in a wide range of tasks such as determining the cultivar identity of seed lots and testing of the distinctness of new cultivars for the award of breeders’ right and cultivar registration. Fast and easy to achieve image-based measurements can thus provide data correlating with genetic properties of germination and growth performance.

Varma et al. reviewed the basics of computer-aided image analysis, which contribute to the gain of insight into seed morphology and biology, in terms of seed size, quality and germination. investigated some moisture dependent physical and mechanical properties of green laird lentil grains namely, grain dimensions, thousand grain mass, surface area, projected area, sphericity, bulk density, true density, porosity, terminal velocity, and static coefficient of friction against different materials. Firatligil-Durmus et al. tested the possibility of applying digital image analysis to the determination of geometrical features of two different varieties (red and green) of lentil grown in Turkey. The measurements of the seed geometrical features were performed using a customized personal computer-based digital image analysis system. Kuo et al. worked on identification of rice grain using image analysis and sparse representation-based classification. They distinguished the rice grains of 30 varieties none destructively using image processing and sparse representation-based classification (SRC). Rice grain images were acquired by microscopy. The morphological, color, and textural traits of the grain body, sterile lemmas, and brush were quantified.

However, from the available literature, it is observed that studies on application of image analysis to seed characterization were all on large seeds such as rice, wheat and coffee, and little information appears to exist on the application of the technique to the characterization of small-sized grains such as caraway and sesame seeds. There is a need for a study to obtain engineering data that are relevant in the processing and handling of these seeds using image analysis.

The main objective of this study was to use image analysis in the evaluation of moisture dependent geometric and gravimetric properties of sesame and black caraway seeds. This involves the extraction of digital images of the seeds at different moisture contents under natural position of rest using a high-resolution digital camera; analysis of the images using image analysis software to obtain axial dimensions and projected area, and determine the volume, mass, bulk density, true density, and porosity of the seeds at different moisture contents.

**Materials and methods**

**Material procurement and preparation**

Sesame (*sesamum indicum* L.) golden brown variety and black caraway (*nigella sativa*) black cumin variety seed-grains used in this study were bought from Maiduguri Monday market, Maiduguri, Borno State, Nigeria. The small-sized grains were cleaned to remove foreign materials, stored in plastic containers and kept under room temperature in the laboratory. The initial moisture contents of the grains were determined using digital Biobase infrared moisture meter.
**Description of experimental set-up and moisture conditioning procedure**

The experimental setup for the study, presented in Figure 3, includes a laptop which was used to control the computer software installed in it and was to take photographic images and stored. A Webcam (Logitech c920) HD camera was used to capture the seed grain images and send them to the computer for storage and further processing. LABVIEW computer software was used to control the camera to capture the images of the small seed grains. The camera was mounted on a Tripod stand. Petri dishes and Plastic Tile plates were used to hold the small grains during the image capturing process. A calibrated meter rule was used to obtain clear readings during image capturing and conversion of pixels to millimeters. Water was added to the small grains in a plastic tile cup to condition the sample and vary the moisture content over time, using a syringe and needle. Bulk quantities of the grains were also poured into a basin containing water and a sample was taken every 15 min for moisture content determination to obtain samples at different moisture levels.

**Methodology**

**Image Capturing:** This involved the use of LABVIEW software to control the camera to capture the image of the small grains via a computer operating in Microsoft Windows operating system. Pre-processing of images was conducted in a program developed by LABVIEW to extract image from the background after which it was used as the ground truth (the image of the grain before being immersed into water). Water was added to the small seed grains at the same reference place to the initial image, for a given period of time to obtain samples at different moisture levels. The system (LABVIEW) was configured to keep taking photographs of the seeds at an interval of 15 minutes using the Webcam camera via the computer. The snapped image was processed using the program developed in LABVIEW and compared with the ground truth to identify differences in area. The procedure was repeated several times and each new outcome was compared to all preceding outcomes. The above methodology was developed and applied in this study after a preliminary study on large seeds, such as mango seeds and palm nuts, showed that it has potential for high accuracy. Figure 4 shows the Image Capturing Flow Diagram indicating how the images were captured and stored on the hard disk of the computer system before being processed in the laboratory.

After the set-up, and the camera on the tripod stand was used to capture the images of seeds that were inside the tile plate by running the programme already installed in the computer system, the images were automatically stored on the hard drive of the computer system. The procedure was repeated for five times at a specified moisture level and up to nine times for each of the two small-sized grains. The seed grains, as placed in the plastic tiles under the camera, are shown in Figure 5. As a precautionary measure, the laboratory atmosphere was modified to eliminate bright light as light caused reflection on the tiles and made processing less successful. There was no use of fans or anything that could trigger airflow, and no shaking of equipment was allowed after the start-up. Visitors or anyone else were not allowed entry so that the experiment would not be interfered with.

**Image processing**

Figure 6 shows the processing flow diagram of the images captured and stored on the hard drive of the computer system.

The description of the operations presented in Figure 6 is as follows. Run: The Run command launched the Image processing program in the LABVIEW software already installed in the system.

Input Image: The images which were already stored on the hard drive of the system, in the RGB form were then inputted into the image processing platform by sending the file containing the saved images to the program in the LABVIEW for the programme to process them automatically. Conversion of the RGB (Red, Green and Blue) Image to Gray Scale Image: The captured images in
Figure 4. Image capturing flow.

Figure 5. Small sized grains in different tile plate, A: sesame seed and B: black caraway seed.
Figure 6. Flowchart for the processing of images captured.
RGB were converted to Gray images. Gray scale images are the digitalized brightness of the pixels of images, and they require less memory for storage and processing. The minimum gray level is 0 while the maximum is 255 levels,\textsuperscript{[19,20]} depending on the digitalization depth of the images. The images are easier to use for further processing when in gray, than the RGB which are color images that take longer time to process. The formula used for the conversion to gray is the average method given in Equation (1).

\[
GS = \frac{(R + G + B)}{3}
\]  

(1)

where: GS is the grayscale, R is red, G is green and B is blue, color bands.\textsuperscript{[21]}

Noise Filter: Noise, which is the deviation of signal from the expected value, is removed/filtered to ensure image quality measurement and this is automatically done by the command already programmed. Conversion to Binary Images: The Gray scale image was converted to binary images (black and white) by first choosing a gray level, T in the original image and then turning every pixel black or white according to whether its gray value is greater than or less than T. This is a single thresholding, calculated using Equation (2).

A pixel becomes

\[
\begin{align*}
0 \text{ white if gray level is } \leq T \\
255 \text{ Black if gray level } \geq T
\end{align*}
\]  

(2)

and this is carried out as shown in Figure 7.

Gray code \[g^3 g^2 g^1 g^0\]

Ex-OR \[\text{Ex-OR} \text{Ex-OR}\]

Binary code \[b^{[1-3]} b^0\]

\[g^3(b^3 \text{ Ex-Org}) (b^2 \text{ Ex-Org}) (b^1 \text{ Ex-Org})\]

Thresholding: This procedure is normally used to remove unnecessary details from an image and it is a vital part of image segmentation. It is carried out to isolate objects from the background and provide a very simple way of showing hidden aspect of an image. The 8-bit grayscale intensity represents the different shades of gray from black to white (ranging from 0 to 255). From the grayscale images of the seeds, pixel values less than 132 were converted to black which is zero (0) and the values higher than 132 were converted to white which is (255). Image thresholding is a simple and effective way of partitioning an image into foreground and background. As a result, the image becomes segmented.

Labeling of seeds: The seeds were labeled for ease of identification automatically by the software – the LABVIEW. Measurements: The seed’s projected area (\(A_p\)) was taken as the area calculated by the algorithm considering the number of pixels within the grain boundary and determining the \(\text{mm}^2\) per pixel.\textsuperscript{[21]} The major axis (a) was the distance between the end points of the longest distance that could be drawn through the seed, and it was determined by computing the pixel distance between every combination of border pixels in the seed boundary while the minor axis (b) was the distance between
the end points of the longest line that could be drawn through the seed that maintains perpendicularly
with the major axis. The aspect ratio was computed as the ratio of the minor axis to the major axis. All
computations were carried out at different moisture levels. End image analysis: The process is ended
and a new image from another seed is inputted.

Stop: The programme and processing activities are stopped and switched off.

**Geometric Properties of Grains**

Preliminary investigations to determine the shape of each of the small-sized grains were carried out
using the data obtained on the axial dimensions at different moisture levels. This involved the
determination of the volume of each grain by the water displacement method as described by
Aviara et al.\textsuperscript{[22]} 1000 grains of each seed were counted and held together with a very thin film of
epoxy resin and submerged in a 5 ml graduated cylinder containing a known volume of water. The
volume displaced divided by 1000 and the outcome was taken as the volume of a single grain when
the error due to the epoxy is considered negligible. Further algebraic manipulation showed that the
grains were oblate spheroidal in shape. This became the adopted shape for the grains in all the
investigations carried out.

The theoretical or experimental or actual volume was taken as the volume obtained from the water
displacement method. For sesame and black caraway seeds at a given moisture content the actual
volume is determined using Equation (3).

\[ V_a = V_2 - V_1 \]  

(3)

where \(V_1\) is the volume of water in the cylinder prior to the immersion of seeds (ml), \(V_2\) is the volume
to which water rose in the cylinder after the seeds were immersed (ml), and \(V_a\) is the volume of water
discharged taken as the actual volume of the seeds (ml). The calculated volume of each grain at a given
moisture level was determined using the equation for the oblate spheroidal object volume given by
Mohsenin\textsuperscript{[23]} represented in Equation (4)

\[ V_c = p a^2 b_s \]  

(4)

where: \(a\) is the semi-major axis, mm; \(b_s\) is the semi-minor axis and \(V_c\) is the calculated volume of the
seed, mm.\textsuperscript{[3]}

The volume correction factor is computed using Equation (5).

\[ k = \frac{V_c}{V_a} \]  

(5)

where: \(V_c\) is the calculated volume, mm\textsuperscript{3}; \(V_a\) is the actual volume measured, and mm\textsuperscript{3} and \(k\) is the
volume correction factor. The axial dimensions of each of the small-sized grains (sesame and black
caraway seeds) obtained from the image analysis at different moisture contents were taken as \(a\), major
axis and \(b\), minor axis.

**Gravimetric properties**

The gravimetric properties include the bulk and true densities, 1000 grain mass and porosity of the
small grains. The bulk density was determined using the AOAC standard method described by Aviara
et al.\textsuperscript{[24,25]} This involved filling a 200 ml cylinder with a sample from a height of 15 cm and weighing
the content. The mass of the bulk sample divided by the cylinder volume was taken as the bulk density
at the specified moisture content. The true density was determined using the water displacement
method described by Dutta et al.\textsuperscript{[26]} and Aviara et al.\textsuperscript{[22]} Porosity was calculated using the relationship
between the true density and bulk density expressed by Jain and Bal\textsuperscript{[27]} as

\[ P = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100\% \]  

(6)
where: P is porosity, %; $\rho_b$ is bulk density, kg/m$^3$ and $\rho_t$ is true density, kg/m$^3$.

**Data and analysis**

All data collected in the study were averaged over five replications at each moisture level. The relationships existing between these properties and grain moisture content were determined using regression models.

**Results and discussion**

**Image capturing and processing**

The images shown in Figures 8 and 9 represent the processing of the small-sized grains from RGB to Gray and binary, after filtering of the noise. They were then subjected to thresholding to reveal hidden aspects of the seeds. The first images were filtered and in Gray scale while the next are in binary and are then segmented and finally labeled.

A similar approach was employed by Khoshroo et al.\(^\text{[28]}\) in the classification of wheat cultivars, Venora et al.\(^\text{[29]}\) in identifying the Italian landrace beans and evaluating the seed size, shape, color and texture of the crop, Gao et al.\(^\text{[30]}\) in determining the shape parameters of rice, and Dell’Aquila\(^\text{[31]}\) in evaluating the germination quality of seeds. Other investigators that applied image analysis techniques to the study geometric and other features of grains include Charytanowicz et al.\(^\text{[32]}\) and Firatligil-Durmus et al.\(^\text{[33]}\) - wheat; Lurstwut and Pornpanomchai\(^\text{[34]}\) and Desai and Rao\(^\text{[35]}\) - rice.

**Geometric Properties**

The values of projected area (Ap), major axis (a), minor axis (b) and aspect ratio (b/a) of sesame seed and black caraway seed determined using image analysis at different moisture contents are presented in Tables 1 and 2, respectively. Tables show that the projected area, major axis, and minor axis of sesame and black caraway seeds increase with increase in grain moisture content. In the moisture range of 2.25–28.5% and 3.04–39.62% for sesame and black caraway seeds, respectively, the projected area increased from 3.3653 to 5.6777 mm$^2$ for sesame and from 1.071 to 5.136 mm$^2$ for black caraway seed. Within the moisture range of 2.25–26.76%, the projected area of sesame seed increased linearly with gradual slope. This may imply that within this moisture range, water imbibition of the seed may have been low and slow, causing moisture content not to have significant influence projected area increase. The projected area continued to increase linearly with moisture content but with more steepy slope after the moisture content of 26.76%. This may indicate that moisture intake and its influence on the increase in projected area of the seed began to be significant. For black caraway seed in the moisture range of 3.04–25.26%, the increase in projected area with moisture content was gradual and exponential, and after that, its increase was still exponential but with a steeper slope. The projected area may have exhibited similar response to moisture intake in both seeds, but the mechanisms of moisture movement and binding to the grain fibrils may have been different.

The relationships existing between the projected area of the seeds can be represented with the following equations.

**Sesame seed**

\[
M : \quad 2.25 - 26.76\% , \quad Ap = 0.0213M + 3.3042 , \quad R^2 = 0.9727 \quad (7)
\]

\[
M : \quad 26.76 - 28.53\% , \quad Ap = 1.0023M - 22.878 , \quad R^2 = 0.9606 \quad (8)
\]

**Black caraway seed**
Figure 8. Captured images of sesame seeds converted from RGB to binary image using the formulas for each conversion and finally labeled.

\[ M : 3.04 - 25.26\%, \quad Ap = 0.9842e^{0.0165M}, \quad R^2 = 0.8965 \]  \hfill (9)

\[ M : 25.26 - 39.62\%, \quad Ap = 0.2189e^{0.0753M}, \quad R^2 = 0.9036 \]  \hfill (10)
where $M$ is moisture content (%) and $A_p$ is projected area ($\text{mm}^2$). Major and minor axes increased from 0.2995 to 0.4521 mm and 0.2872 to 0.4461 mm for sesame seeds in the moisture range of 2.25–28.53% and for caraway seeds in the moisture ranges of 3.04–39.63%, they increased from 0.2295 to 0.3774 mm and 0.2269 to 0.3731 mm, respectively. Within the moisture range of 2.25–26.9%, the major and minor axes of sesame seed increased linearly with moisture content, and in the moisture range of 26.9–28.53%, each of the axes increased in a polynomial trend with moisture content. For the

Figure 9. Captured images of black caraway seeds converted from RGB to binary image using the formulas for each conversion and finally labeled.
black caraway seed, in the moisture range of 3.04–35.11%, the two axial dimensions increased linearly with moisture content, and while the major axis thereafter, increased logarithmically with moisture content, the minor axis maintained linear increase but having steeper slope. The factors that controlled the response of projected area to moisture increase in both seeds may have been at play in the major and minor axes. The following mathematical expressions can be used to describe the relationships existing between the axial dimensions of the seeds and seed moisture content.

Sesame seed

\[ M : 2.25 - 26.9\%, \quad a = 0.0022M + 0.2896, \quad R^2 = 0.8705 \quad (11) \]

\[ M : 26.9 - 28.53\%, \quad a = 0.0576M^2 - 3.131M + 42.949, \quad R^2 = 0.9989 \quad (12) \]

\[ M : 2.25 - 26.9\%, \quad b = 0.0015M + 0.281, \quad R^2 = 0.9072 \quad (13) \]

\[ M : 26.9 - 28.53\%, \quad b = 0.0586M^2 - 3.1739M + 43.288, \quad R^2 = 0.9984 \quad (14) \]

Black caraway seed

\[ M : 3.04 - 35.11\%, \quad a = 0.0014M + 0.2247, \quad R^2 = 0.9767 \quad (15) \]

\[ M : 35.11 - 39.62\%, \quad a = 0.7362Ln(M) - 2.3245, \quad R^2 = 0.8311 \quad (16) \]

\[ M : 3.04 - 35.11\%, \quad b = 0.001M + 0.225, \quad R^2 = 0.9624 \quad (14) \]

\[ M : 35.11 - 39.62\%, \quad b = 0.00284M - 0.7475, \quad R^2 = 0.9238 \quad (15) \]

where: a is major axis, mm and B are the minor axis (mm). The aspect ratio of each of the seeds decreased with increase in moisture content down to a point and increased with further increase in moisture content. At a similar moisture level, the sesame seed is larger than the black caraway seed.
The measured (Va) and calculated (Vc) volumes as well as the volume correction factor (k) of the seeds at different moisture contents are presented in Table 3 for sesame and Table 4 for black caraway seed. From the Tables, it can be seen that the volume of the seeds and volume correction factor increased with increase in moisture content. Experimental volume of sesame seed increased gradually and exponentially with moisture content in the moisture range of 2.25–26.76%. It thereafter increased steeply maintaining the exponential trend. In the whole moisture range of 3.04–39.62%, the experimental volume of black caraway seed increased exponentially with increase in moisture content. The relationship existing between experimental (actual) volume, Va and moisture content, M can be expressed with the following Equations.

Sesame

\[
M : 2.25 - 26.76\%, \quad Va = 0.0206e^{0.008M}, \quad R^2 = 0.8127 \quad (16)
\]

\[
M : 26.76 - 28.53\%, \quad Va = 0.003e^{0.0812M}, \quad R^2 = 0.7556 \quad (17)
\]

Black Caraway seed

\[
Va = 0.7008e^{0.0423M}, \quad R^2 = 0.8275 \quad (18)
\]

**Gravimetric properties**

The variation of 1000 grain mass, W1000 of sesame and black caraway seeds with moisture content is, respectively, shown in Figure 10. From this Figure, it can be seen that the 1000 grain mass of the seeds increased linearly from 2.9043 to 3.8743 g and 2.644 to 3.7805 g with moisture content in the moisture ranges of 2.25–28.53% for sesame and 3.04–39.62% for black caraway seeds, respectively. The relationship existing between 1000 grain mass and grain moisture content can be represented with Equations (19) and (20).

**Table 3.** Measured and calculated volumes and volume correction factor of sesame seed at different moisture contents.

| MC %   | Va mm³ | Vc mm³ | k  |
|--------|--------|--------|----|
| 2.25   | 0.0214 | 0.0182 | 0.851 |
| 18.80  | 0.0227 | 0.0194 | 0.853 |
| 24.25  | 0.0242 | 0.0207 | 0.855 |
| 25.68  | 0.0261 | 0.0224 | 0.857 |
| 26.76  | 0.0265 | 0.0227 | 0.857 |
| 26.90  | 0.0267 | 0.0229 | 0.857 |
| 27.93  | 0.027  | 0.0232 | 0.86 |
| 28.15  | 0.0289 | 0.0249 | 0.861 |
| 28.53  | 0.0317 | 0.0274 | 0.865 |

**Table 4.** Measured and calculated volumes and volume correction factor of black caraway seed at different moisture contents.

| MC %   | Va mm³ | Vc mm³ | k  |
|--------|--------|--------|----|
| 3.04   | 0.01   | 0.0085 | 0.85 |
| 23.40  | 0.0104 | 0.00894 | 0.86 |
| 25.26  | 0.0109 | 0.0094 | 0.86 |
| 35.11  | 0.0112 | 0.0098 | 0.87 |
| 36.05  | 0.0144 | 0.0126 | 0.874 |
| 36.94  | 0.024  | 0.021 | 0.876 |
| 37.50  | 0.025  | 0.0219 | 0.878 |
| 38.75  | 0.0274 | 0.0241 | 0.878 |
| 39.62  | 0.0283 | 0.0249 | 0.879 |
where: \( W_{1000s} \) is 1000 grain mass of sesame seed, g and \( W_{1000c} \) is 1000 grain mass of black caraway seed, g. At a similar moisture level, sesame seed is heavier than black caraway seed.

The effect of moisture content on the particle density of sesame and black caraway seeds is, respectively, presented in Figure 11. Particle density of both grains decreased linearly from 828.6 to 378.4 kg/m\(^3\) in the moisture range of 2.25–28.53% for sesame, and from 746.4 to 295.5 kg/m\(^3\) for black caraway seed in the moisture range of 3.04–39.62%. The relationship existing between the particle density of the seeds and grain moisture content can be described using Equations (21) and (22).

\[
\rho_{ts} = 871.55 - 17.422MR^2 = 0.996
\]  

(21)
\[ \rho_{tc} = 765.45 - 12.297MR^2 = 0.983 \]  

where: \( \rho_{ts} \) is the true density of sesame seed, kg/m\(^3\), and \( \rho_{tc} \) is the true density of black caraway seed, kg/m\(^3\).

The variation of the bulk density of the seeds with moisture content is shown in Figure 12. Bulk density of the sesame seed decreased linearly from 502.1 kg/m\(^3\) to 310.87 kg/m\(^3\) as the moisture content of the seed increased from 2.25 to 28.53% while that of black caraway seed decreased from 560 kg/m\(^3\) to 295.5 kg/m\(^3\) in the grain moisture range of 3.04–39.62%. At a similar moisture level, the bulk density of caraway seed is higher than that of the sesame. The following Equations can be used to express the relationship existing between the bulk density of the seeds and grain moisture content.

\[ \rho_{bs} = 516.37 - 7.4038MR^2 = 0.9941 \]  

\[ \rho_{bc} = 577.81 - 8.1654MR^2 = 0.9915 \]

where: \( \rho_{bs} \) is the bulk density of sesame seed, kg/m\(^3\), and \( \rho_{bc} \) is the bulk density of black caraway seed, kg/m\(^3\).

The effect of moisture content on the porosity of sesame and black caraway seeds is, respectively, shown in Figure 13. From the Figure, it can be seen that for each grain, the porosity decreases polynomially with moisture content. In the moisture range of 2.25–28.53%, the porosity of sesame seed decreased from 39.4038% to 17.8462% and from 24.9732% to 8.6971% for black caraway seed in the moisture range of 3.04–39.62%. The relationship existing between the porosity of the seeds and the grain moisture content can be described using Equations (25) and (26).

\[ P_s = -0.0433M^2 + 0.5115M + 38.506, \quad R^2 = 0.9938 \]  

\[ P_c = -0.0122M^2 + 0.1058M + 24.547, \quad R^2 = 0.9073 \]

where: \( P_s \) is the porosity of sesame seed, % and \( P_c \) is the porosity of black caraway seed, %.

*Figure 12.* Variation of bulk density of sesame and black caraway seeds with moisture content.
Conclusion

The investigation of moisture dependence of geometric and gravimetric properties of sesame and black caraway seeds revealed the following. (i) It was possible to determine the geometric and gravimetric properties of the seeds using image analysis. (ii) The major and minor axial dimensions of the seeds could be accurately determined using image analysis. As the moisture content of the seeds increased, the dimensions also increased. (iii) The seeds were oblate spheroidal in shape, with grain projected area, volume, and volume correction factors that increased with increase in moisture content. (iv) 1000 grain mass increased with moisture content. (v) Particle and bulk densities and porosity of the seeds decreased with increase in moisture.

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Figure 13. Effect of moisture content on porosity of sesame and black caraway seeds.
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