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GEOMETRIC MODELS FOR ANALYZING THE SHAPE OF CAULIFLOWER HEADS

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A b s t r a c t

Selected geometric properties of cauliflower heads cv. *Gohan F1* were analyzed by building numerical models with the use of a 3D scanner. Geometric models of cauliflower heads were developed in ScanStudio HD PRO, FreeCAD, and MeshLab programs. Five geometric models describing the shape of cauliflower heads were generated with the use basic geometric figures and drawing tools in FreeCAD. The geometry of numerical models and geometric models was compared in GOM Inspect. The surface area, volume, and detailed geometric dimensions of the developed models were determined. The deviations in cauliflower dimensions calculated by geometric models were mapped. The surface area, volume, and geometric dimensions of cauliflower heads were most accurately represented by the model generated with the Quadric Edge Collapse Decimation (QECD) function. In this model, the relative error of surface area measurements did not exceed 5%, and the relative error of volume measurements did not exceed 4%. This model was also characterized by the smallest average maximum deviation (+) and the smallest average minimum deviation (-) which was estimated at 8%. The proposed geometric model can be used for research and design purposes.

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Introduction

Cauliflowers are widely recognized for their chemical composition, health benefits, and attractive taste. Cauliflowers contain sodium, potassium, magnesium, calcium, manganese, iron, copper, zinc, phosphorus, fluoride, chlorine, iodine, carotenes, vitamins K, B1, B2, B6, and C, as well as nicotinic and pantothenic acids. These vegetables are immensely popular on account of their nutritional value and year-round availability. Fresh cauliflowers are available during the growing season, whereas frozen cauliflowers can be purchased in the remaining seasons of the year. The edible part of the cauliflower is the head or the curd which consists of a compact and fleshy inflorescence meristem. The mass of a cauliflower head ranges from 0.25 kg to 2 kg (FLORKIEWICZ et al. 2014, NASRINA et al. 2022, OLESEN 1997). Heads are partly covered by leaves that grow out of the stem. Cauliflowers are harvested manually or with the use of semi-automated harvesting systems. Manual harvesting is laborious and not highly efficient. In small farms, cauliflowers are harvested with the use of wheeled platforms and conveyor belts connected to a tractor. Complex harvesting machines that separate cauliflower heads into florets are applied in large plantations. Research has been conducted to improve the performance of cauliflower harvesting and processing devices, and the initial stage of the design process involves computer simulations. Numerical models are generated to plan cauliflower processing operations (ANDUJAR at al. 2016).

Food and agricultural products are modeled to design farming machines and equipment, and the applied processing technology should be considered in the modeling process (DATTA, HALDER 2008). Technological processes can be designed based on numerical 3D models of agricultural products that accurately describe their geometric and physical properties. Traditional numerical models are developed on the assumption that agri-food products are homogeneous and isotropic, and these products are modeled with the use of regular shapes and figures (such as a cylinder, a sphere, or a cone) (GASTÓN et al. 2002, SINNOTT et al. 2021). Modern software tools for computer-aided design (CAD) and computational fluid dynamics (CFD) modeling are applied to simulate complex operations during the processing of agri-food products (VERBOVEN et al. 2004, LONG et al. 2020, BECERRA et al. 2022, SHUAI et al. 2022). The generation of models that accurately depict the parameters of individual products and can be reliably used in computer simulations pose a challenge in research and design of agri-food processing machines (JIAN et al. 2020). The development of numerical models that accurately describe a product's shape is a difficult and laborious task (GONI et al. 2007, JADWISIEŃCZAK, KALINIEWICZ 2011). Many researchers rely solely on image analysis software or instruments such as calipers and micrometers to measure fruit and seeds (FRĄCZEK, WRÓBEL 2006, SZWEDZIAK, RUT 2008).

Traditional and advanced measuring techniques for building accurate models of agri-food products have been described in many studies. CROCOMBE et al. (1999) used a laser scanner to analyze the surface of meat pieces and develop a numerical model for simulating meat refrigeration time. JANCSOK et al. (2001) relied on a machine vision system to generate numerical models of pears cv. Konferencja. SABLIOV et al. (2002) proposed an image analysis method for measuring the volume and surface area of axially symmetric agri-food products. SCHEERLINCK et al. (2004) designed a thermal system for disinfecting fruit surfaces based on a 3D model of strawberries generated in a machine vision system. KIM et al. (2007) proposed a methodology for generating 3D geometric models of irregularly shaped food products with the use of computed tomography. GONI et al. (2008) relied on magnetic resonance imaging to model the geometric properties of objects. SIRIPON et al. (2007) used a 3D scanner (Atos, GOM, Germany) to analyze chicken half-carcasses and simulate cooking processes. Computer models depicting the shape of carrots, apples cv. Jonagored, and chicken eggs were generated by MIESZKALSKI (2013). The cited author applied Bézier curves to describe the shape of biological objects. The obtained mathematical models were used to generate 3D figures that accurately depicted the shape and basic dimensions of the analyzed objects. BALCERZAK et al. (2015) modeled the geometric properties of corn and oat kernels in the 3ds Max environment. The authors obtained geometric data, generated meshes, and calculated nodal coordinates based on the acquired images of kernel cross-sections. JIANGANG et al. (2021) phenotyped potato tubers with the use of a 3D imaging system. The rapid characterization of vegetation structure with a Microsoft Kinect Sensor was described by AZZARI et al. (2012).

A review of the literature indicates that various imaging techniques can be applied to model irregularly shaped products. 3D scanners are increasingly used to develop numerical models that accurately depict the shape of the examined objects. These models can be deployed to analyze the shape of entire objects or their parts (RAHMI, FERRUH 2009, ANDERS et al. 2015, BORYGA, KOŁODZIEJ 2022). Therefore, the aim of this study was to develop numerical models of cauliflower heads with the use of a 3D scanner and to build geometric models using basic geometric figures and drawing tools in CAD software. The resulting geometric models were compared based on the surface area, volume, and dimensions of rendered cauliflower heads. It should be noted that software tools supporting the calculation of deviations in linear measurements have never been used in research to compare geometric models of agricultural products.

Materials and methods

The experiment was conducted on cauliflower heads cv. *Gohan F1* produced in a privately-owned farm in Zakrzewek, Sompolno municipality, Poland (52.3393°N, 18.5325°E). This cultivar is highly popular in north-eastern Poland. Cauliflowers cv. *Gohan F1* are cultivated by many farmers in the region and sold on the local market. In the farm, cauliflowers were grown on an area of approximately 0.5 ha, and the entire produce was sold. Thirty cauliflower heads without visible signs of damage were randomly selected for the study. Cauliflower heads were hard and dense, with a fairly similar, mushroom-like shape. Cauliflowers were harvested between 6 a.m. and 8 a.m. to supply fresh and supple plant material for each experiment. The harvested heads were stored in a refrigerator for up to two days at a constant temperature of 6±1°C until 3D scanning. Cauliflowers were harvested on six dates in the second half of June 2022, and five heads were acquired during each sampling session. Each sampling session involved five cauliflowers due to the operating speed of the 3D scanner. An accurate model of a cauliflower head was developed within approximately 1.5 hours. The length, width, and thickness of cauliflower heads were measured with a digital caliper with an accuracy of d=0.01 mm (Fig. 1).

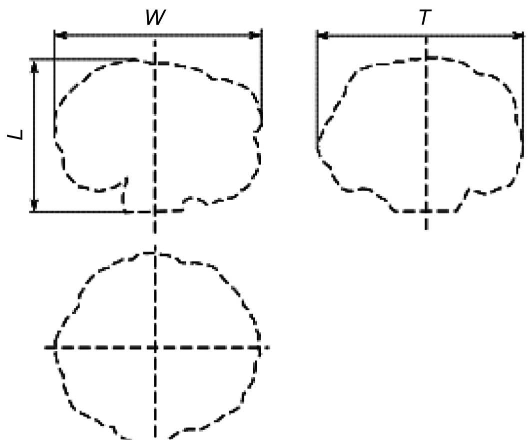

Fig. 1. View of a cauliflower head: L – length [mm], W – width [mm], T – thickness [mm]

The construction of numerical models of cauliflower heads was made using a 3D laser scanner by Nextengine (http://www.nextengine.com). Cauliflower heads cleaned of leaves were attached to a turntable with a handle before scanning. When scanning heads, the normal mode was used, and the distance between the samples and the scanner was 43 cm. For each head, 9 side scans were made, plus an additional scan of the top and bottom of the head. Cauliflowers were scanned with the resolution of 15 pixels per mm^2, and pixel size of 0.13 mm. The average time of performing all the scans that made up the numerical model was about 30 minutes. Numerical 3D models of cauliflower heads were developed by combining scanned images in ScanStudio HD PRO (http://www.nextengine.com). The surface area and volume of cauliflower heads were determined in MeshLab (http://meshlab.sourceforge.net/). The surface area and volume of geometric models were also calculated (Fig. 2) in five different ways.

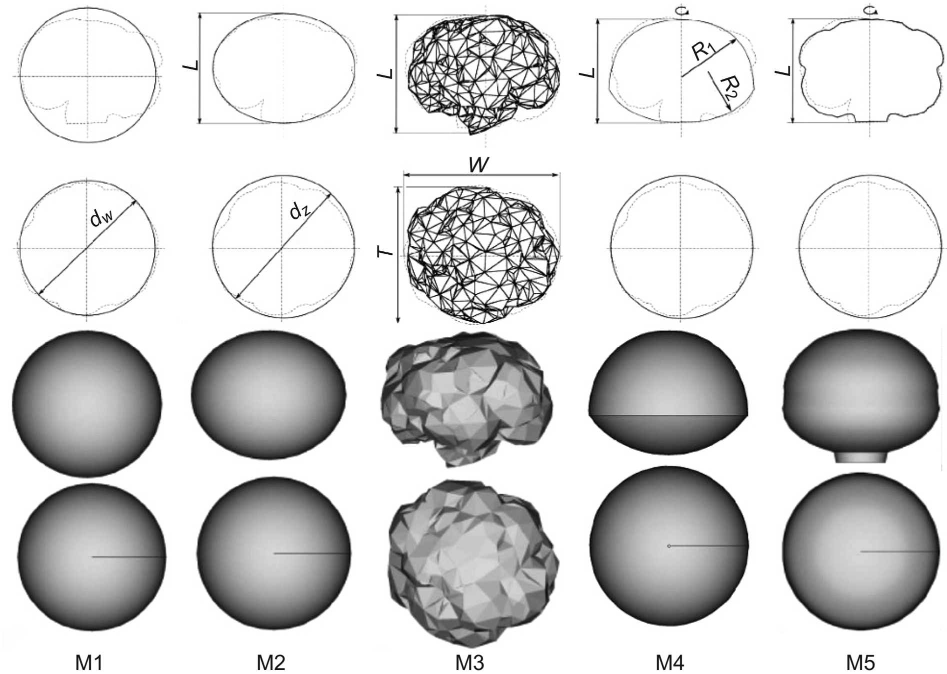

Fig. 2. Geometric models of a cauliflower head: M1 – sphere, M2 – rotational ellipsoid (spheroid), M3 – model generated with the QECD function, M4 – model generated as a solid of revolution based on a contour drawn with an arc tool, M5 – model generated as a solid of revolution based on a contour drawn with the use of a complex curve, L – length [mm], W – width [mm], T – thickness [mm], R_1 – arc radius [mm], R_2 – arc radius [mm]

The volume and surface area of cauliflower heads were calculated with the following formulas:

– sphere model (M1):

$$A_{M1} = \pi \cdot d_w^2 \tag{1}$$

$$V_{M1} = \frac{\pi \cdot d_w^3}{6} \tag{2}$$

– rotational ellipsoid (spheroid) model (M2):

if: $$\frac{L}{2} > \frac{d}{2},$$

then:

$$A_{M2} = \frac{4 \cdot \pi \cdot d_z^2 + \pi \cdot L \cdot d_z \cdot e \cdot \arcsin(e)}{8} \tag{3}$$

where:

$$e = \sqrt{1 - \frac{d_z^2}{L^2}} \tag{4}$$

$$V_{M2} = \frac{\pi \cdot d_z^2 \cdot L}{6} \tag{5}$$

Geometric mean diameters in models M1 and M2 were determined with the below formulas:

$$d_w = \frac{L + W + T}{3} \tag{6}$$

$$d_z = \frac{W + T}{2} \tag{7}$$

Geometric model M3 comprising a simplified triangle mesh was generated with the Quadric Edge Collapse Decimation (QECD) function (THAKUR et al. 2009). This model was obtained by reducing the number of points in the numerical 3D model generated with the use of a 3D scanner. The mesh in the numerical model was simplified with the use of the Quadric Edge Collapse Decimation function in MeshLab v. 1.3.3 (CIGNONI et al. 2008). The obtained numerical 3D models consisted of 310,059+/-170,002 points on average (coefficient of variation – 54.81), and the geometric models simplified with the QECD function consisted of 923+/-294 points on average (coefficient of variation – 31.93). The surface area and volume of the generated models were determined in MeshLab.

Geometric model M4 of a cauliflower head was a solid of revolution that was generated based on a contour drawn with an arc tool. The images were downloaded in FreeCAD. Cauliflowers were photographed with the Casio EX-F1

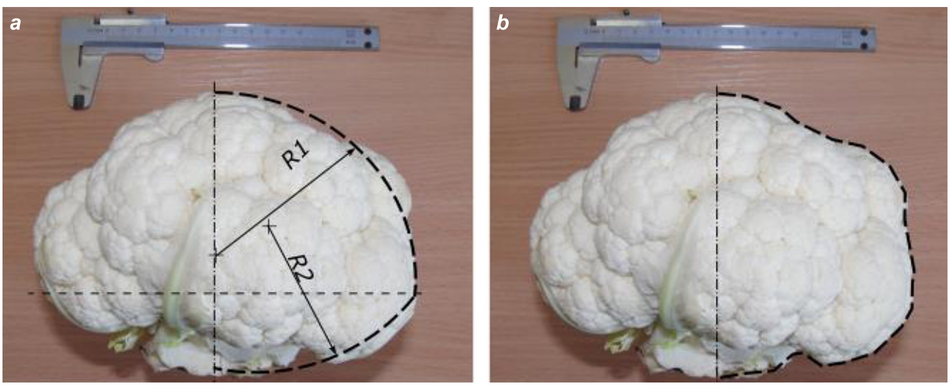

Fig. 3. Model generated: *a* – based on a contour drawn with an arc tool, *b* – based on a contour drawn with the use of a complex curve

digital camera, and the obtained images had a resolution of 2,816 × 2,112 pixels. The camera was mounted on a tripod, and it was positioned 50 cm above the cauliflower head. The contour of the cauliflower head was drawn with an arc tool based on the location of three points. The measurements produced two arcs with R_1 and R_2 radii (Fig. 3*a*).

Geometric model M5 of a cauliflower head was a solid of revolution that was generated by drawing a contour with the use of a complex curve in FreeCAD (Fig. 3*b*) The surface area and volume of the acquired geometric models were determined with the FCInfo tool in FreeCAD (https://www.freecadweb.org). The geometry of numerical and geometric models were compared in GOM Inspect (http://www.gom.com). The length, width, and thickness of cauliflower heads were measured with a caliper. Cauliflower mass was determined with the use of the Radwag WPS 3100/C/2 weighing scale to the nearest 0.1 g. The results were processed with the use of basic statistics and the Kruskal-Wallis non-parametric test. Data were checked for normal distribution and the homogeneity of variance in Levene's test. Data were processed statistically at a significance level of $\alpha = 0.05$ in Statistica 13.3.

Results and discussion

Cauliflower heads cv. *Gohan F1* are composed of tightly packed florets on a short stem. Green leaves grow out of the stem below the head. This cauliflower variety produces white-colored heads. The mass of cauliflower heads ranged from 469.3 g to 1,502.4 g. Based on the results of 3D scanning (Fig. 4), the surface area

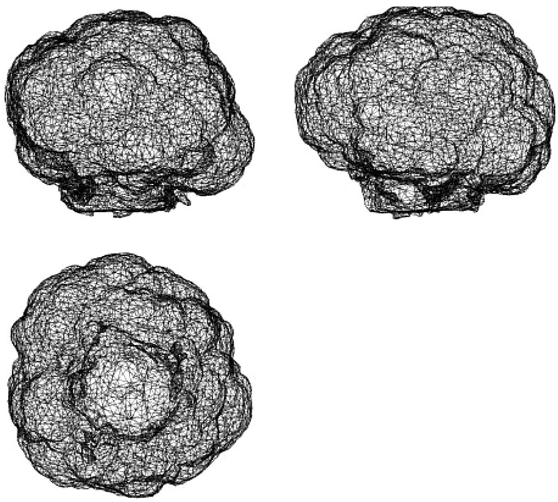

Fig. 4. Numerical model of a cauliflower head comprising a triangle mesh

of cauliflower heads was determined in the range of 521.29 cm^2 to 1,308.41 cm^2 (856.99 cm^2 on average), and head volume ranged from 745.95 cm^3 to 2,625.19 cm^3 (1,418.16 cm^3 on average) (Tab. 1). The average dimensions, surface area, and volume of the analyzed cauliflower heads are presented in Table 1.

Table 1

Geometric parameters of cauliflower heads

Parameter	Average	Range	Standard deviation
L [mm]	130.68	10.44	13.65
W [mm]	157.09	10.66	16.74
T [mm]	148.56	12.29	18.26
A^{3D} [cm^2]	856.99	21.92	187.89
V^{3D} [cm^3]	1,418.16	32.76	464.59

^{3D} – 3D scanning

Significant differences between the average surface area and average volume of cauliflower heads were determined by the Kruskal-Wallis non-parametric test. Significant differences in the parameters of cauliflower heads determined with the use of 3D scanning, mathematical formulas, and geometric models are presented in Tables 2 and 3. The average surface area of cauliflower heads determined based on the numerical 3D model did not differ significantly from that determined in geometric model M3, but it differed significantly from the average surface area in geometric models M1, M2, M4, and M5. The sphere model M1 and the rotational ellipsoid model M2 did not account for concave and convex areas on the surface of cauliflower heads. These areas were partly considered in the models generated as solids of revolution (M4 and M5), but modeling accuracy was determined by the head profile selected for drawing contours. The adopted modeling approach considerably influenced the surface area of the model.

Table 2

Significance of differences in the average surface area of cauliflower heads; multiple comparison test

Method of measurement	Valid N	Sum of ranks	Mean rank	Mean
3D	30	3,894.00	129.80	856.99^{a}
M1	30	2,522.00	84.06	670.08^{b}
M2	30	640.00	21.33	409.08^{c}
M3	30	3,555.00	118.50	812.95^{a}
M4	30	2,899.00	96.63	715.04^{b}
M5	30	2,780.00	92.66	704.78^{b}

Surface area A (Kruskal-Wallis test), H (5, N = 180) = 79.51622; p = 0.000; values with the same letters in columns do not differ significantly; a, b, c – $P \leq 0.05$.

The average volume of cauliflower heads determined based on the numerical 3D model did not differ significantly from that determined based on sphere model M1, rotational ellipsoid (spheroid) model M2, model M3 developed with the QECD function, model M4 of a solid of revolution generated based on a contour drawn with an arc tool, and model M5 of a solid of revolution generated based on a contour drawn with the use of a complex curve.

Concave and convex areas on the surface of cauliflower heads were not considered in the sphere model M1, the rotational ellipsoid model M2, or the models generated as solids of revolution (M4 and M5), but the above did not significantly affect the volume of the obtained models. Model M3, a triangle mesh with a reduced number of nodes, well depicted the surface area and the volume of a cauliflower head, compared with an accurate 3D scan, but it. The adopted modeling method had a less profound impact on the volume of the generated model.

Table 3

Significance of differences in the average volume of cauliflower heads; multiple comparison test

Method of measurement	Valid N	Sum of ranks	Mean rank	Mean
3D	30	2,335.00	77.83	1,418.16^{a}
M1	30	3,106.00	103.53	1,650.95^{a}
M2	30	3,012.00	100.40	1,628.98^{a}
M3	30	2,150.00	71.66	1,367.21^{a}
M4	30	2,777.00	92.56	1,583.44^{a}
M5	30	2,910.00	97.00	1,655.76^{a}

Volume V (Kruskal-Wallis test), H (5, N = 180) = 9.166163; p = 0.1026; values with the same letters in columns do not differ significantly; a, b, c – $P \leq 0.05$.

The distribution of surface area values measured with the use of a 3D scanner and the developed geometric models is presented in Figure 5*a*. The distribution of volume values measured with the same methods is presented in Figure 5*b*.

Assuming that cauliflower heads are accurately measured with a 3D scanner, the resulting data can be used as a reference to compare the results of digital caliper measurements and to describe the shape of cauliflower heads with the use of the generated geometric models. The relative error between the values obtained in the 3D model and geometric models was referred to as a measurement error. The error in surface area measurements was smallest (5%) in geometric model M3. Relative error was determined at 16% in geometric model M4 of a solid of revolution generated based on a contour drawn with an arc tool, and at 18% in geometric model M5 of a solid of revolution generated based on a contour drawn with the use of a complex curve (Fig. 6*a*). The error in volume measurements was smallest (≤ 4%) in model M3, and it reached 12% and 15% in models M4 and M5, respectively (Fig. 6*b*).

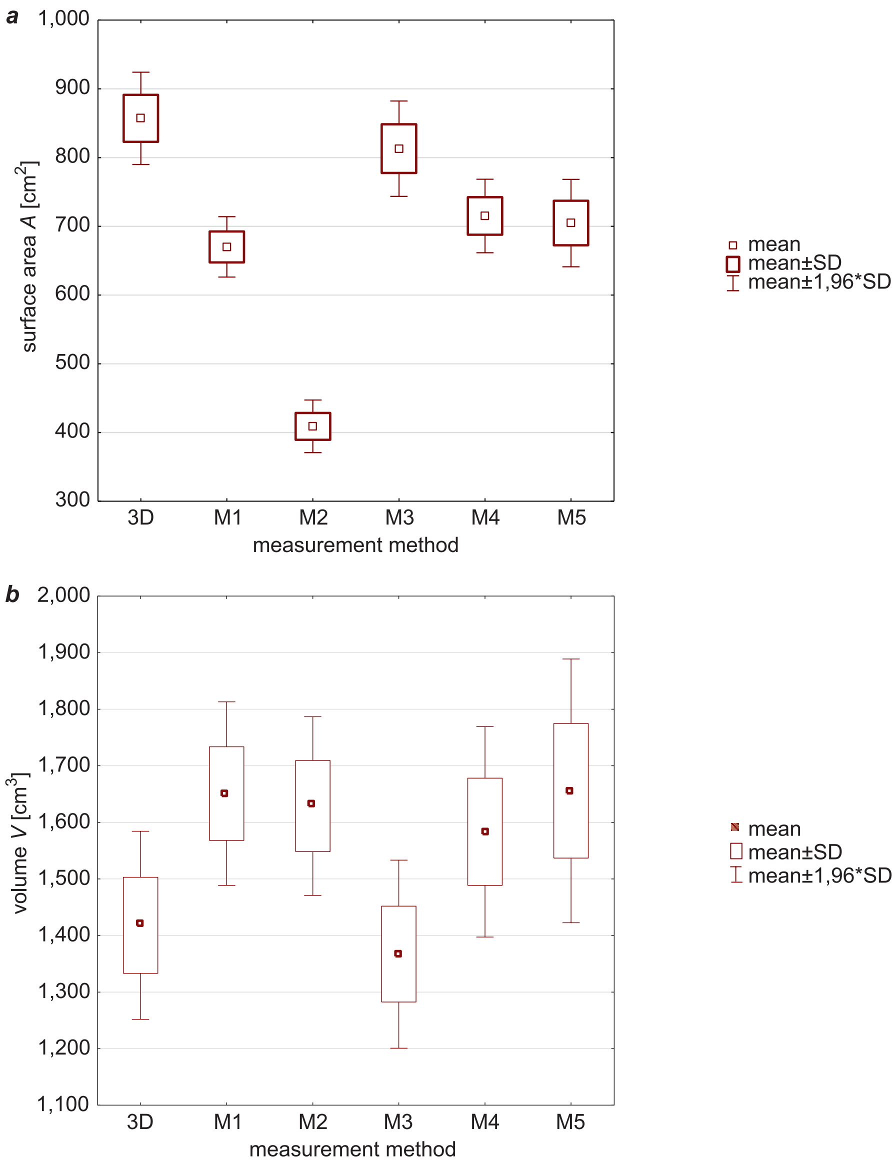

Fig. 5. Parameters of the normal distribution of:
a – surface area values, *b* – volume values

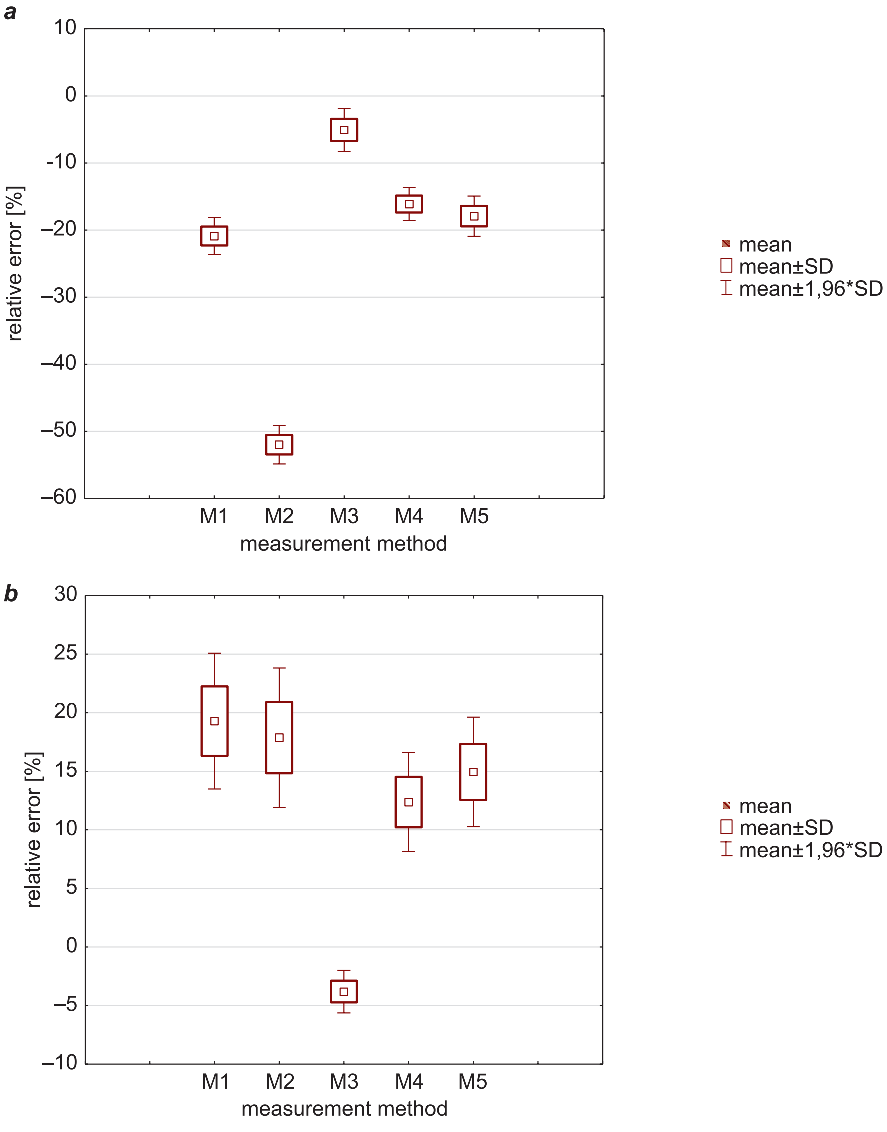

Fig. 6. Relative error of: *a* – surface area measurements in geometric models and the 3D model, *b* – volume measurements in geometric models and the 3D model

The deviations between the dimensions of cauliflower heads measured with the use of geometric models and the 3D model were computed in GOM Inspect (https://www.gom.com) (Fig. 7). In Figure 7 areas marked in green show places where deviations are close to zero, while areas marked in blue and red show places with the greatest deviations.

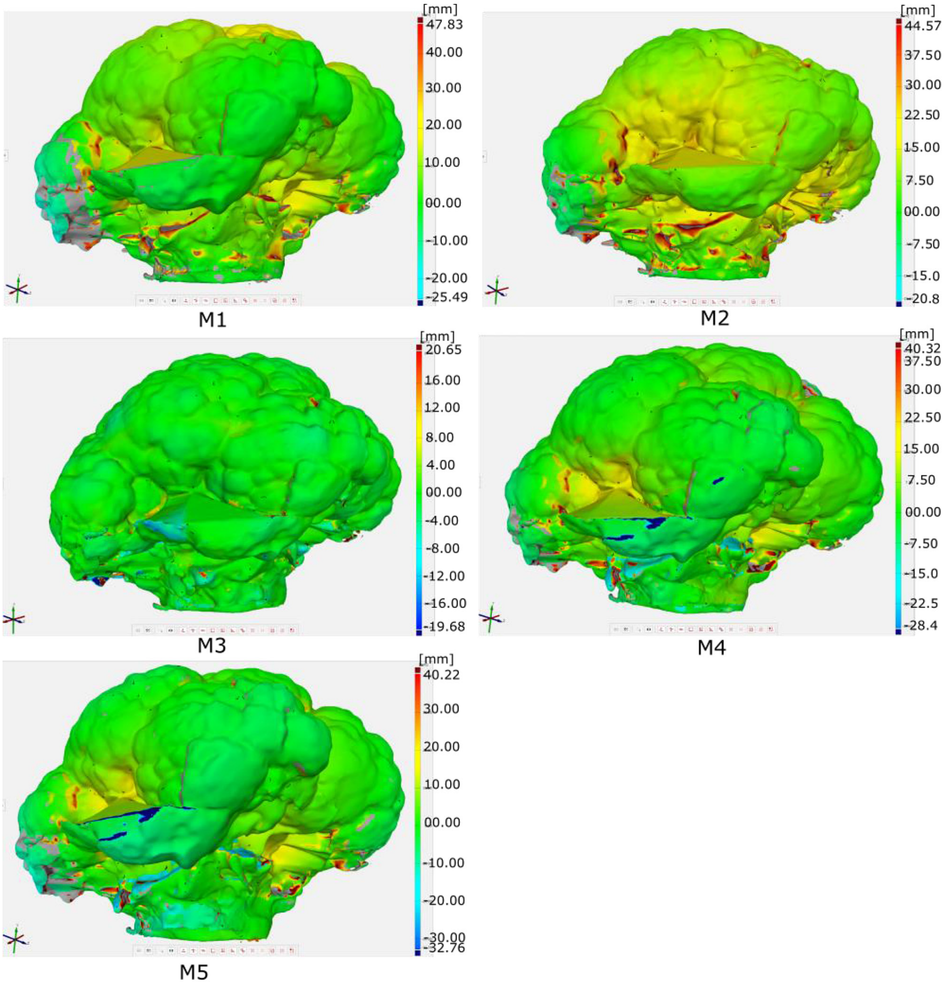

Fig. 7. Maps of deviations in the dimensions of cauliflower heads measured with the use of different models: M1 – sphere, M2 – rotational ellipsoid (spheroid), M3 – geometric model developed with the QECD function, M4 – geometric model of a solid of revolution generated based on a contour drawn with an arc tool; M5 – geometric model of a solid of revolution generated based on a contour drawn with the use of a complex curve

The distribution of maximum (+) and minimum (-) deviations in cauliflower dimensions measured with the use of geometric models and the numeric model is presented in Figures 8*a* and 8*b*.

The smallest average maximum deviation (+) in cauliflower parameters was noted in geometric model M3 at 12.63 mm. The average maximum deviation (+) of the parameters calculated in geometric models M1, M2, M4, and M5 ranged

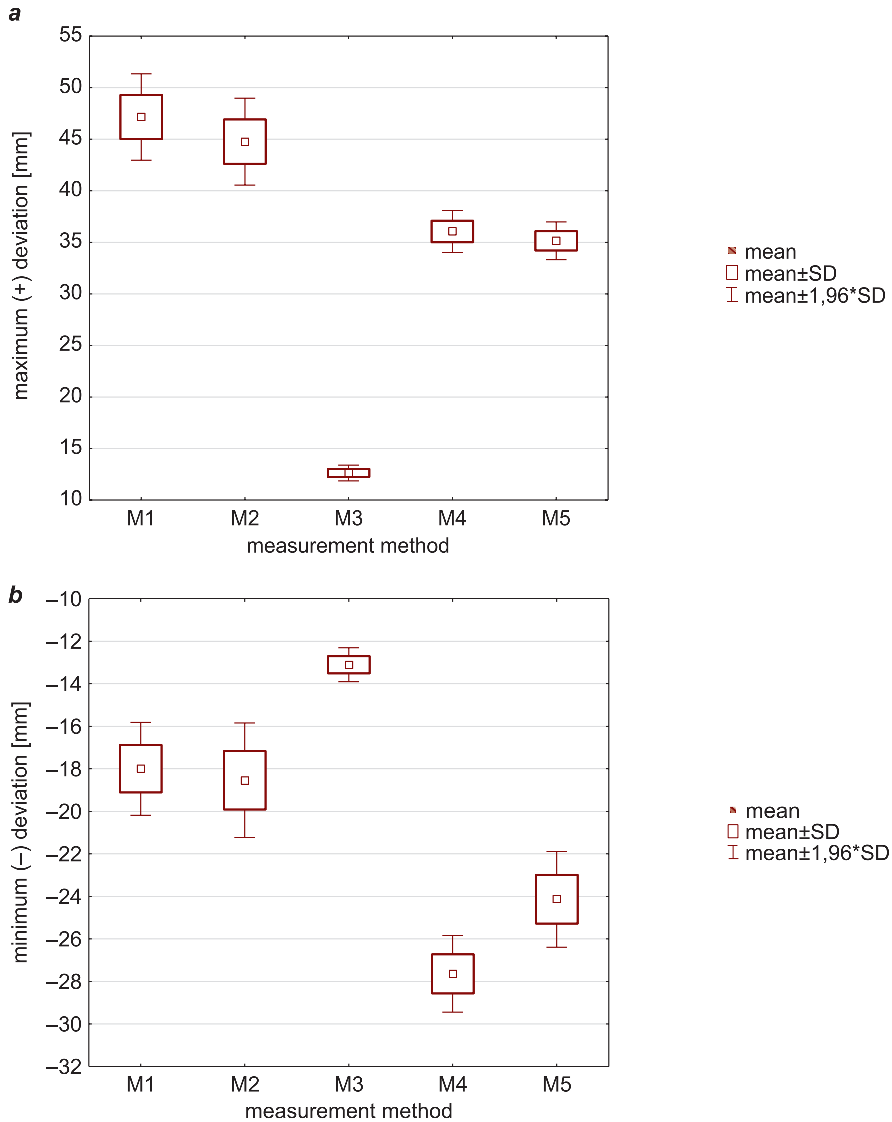

Fig. 8. Parameters of the normal distribution: *a* – of maximum (+) deviation values, *b* – of minimum (-) deviation values

from 35.15 mm to 47.15 mm (Tab. 4). The smallest average minimum deviation (-) in cauliflower parameters was observed in geometric model M3 at -13.10 mm. The average minimum deviation (-) of the parameters calculated in geometric models M1, M2, M4, and M5 ranged from -17.99 mm to -27.64 mm (Tab. 5).

Table 4

Significance of differences in average maximum deviation (+) in geometric models of cauliflower heads; multiple comparison test

Method of measurement	Valid *N*	Sum of ranks	Mean rank	Mean
M1	30	3,413.50	113.78	47.15^{a}
M2	30	3,120.50	104.01	44.77^{a}
M3	30	465.00	15.50	12.63^{b}
M4	30	2,236.50	74.55	36.05^{c}
M5	30	2,089.50	69.65	35.15^{c}

Maximum deviation (+) (Kruskal-Wallis test), H (4, N = 150) = 93.99788; p = 0.000; values with the same letters in columns do not differ significantly; a, b, c – $P \leq 0,05$

Table 5

Significance of differences in average minimum deviation (-) in geometric models of cauliflower heads; multiple comparison test

Method of measurement	Valid *N*	Sum of ranks	Mean rank	Mean
M1	30	2,623.00	87.43	-17.99^{a}
M2	30	2,611.00	87.03	-18.53^{a}
M3	30	3,560.00	118.66	-13.10^{b}
M4	30	996.00	33.20	-27.64^{c}
M5	30	1,535.00	51.16	-24.13^{d}

Minimum deviation (-) (Kruskal-Wallis test), H (4, N = 150) = 71.84437; p = 0.000; values with the same letters in columns do not differ significantly; a, b, c, d – $P \leq 0,05$

In the articles listed in the references, the authors built and used geometric models of raw materials, but these models were not verified in terms of matching them to real objects. The example of building a geometric model of a cauliflower heads shows the possibility of checking how the built model is matched to the real object. This may be important in some cases of simulation studies. ANDUJAR et al. (2016) used a Kinect sensor which supports rapid scanning of objects in real time and can be applied in field studies. However, the generated models are not highly accurate. BALCERZAK et al. (2015) relied on photographs to generate a triangular mesh model of corn grains which are much smaller and have smoother surfaces than cauliflower heads. This technique is relatively simple, but it requires certain experience. GONI et al. (2007) modeled meat pieces and apples cv. Red Delicious. In the cited study, the reconstructed object was divided into slices, contours were drawn around each slice, and the results were used to build a 3D model. BALCERZAK et al. (2015) and GONI et al. (2007) used complex curves in certain stages of the modeling process.

Conclusions

Building numerical models of cauliflower heads using 3D scanning, geometric models using basic geometric solids and geometric models built on the basis of available drawing functions in CAD software allowed to compare selected geometric parameters. Parameters such as surface area, volume and dimensions were compared. The use of the above-mentioned software and the 3D scanning method allows to build more advanced models of natural resources. The obtained results allow to formulate the following conclusions:

1. The surface area of cauliflower heads can be most accurately determined with the use of geometric models where the relative error of measurement does not exceed 5%. The above criterion was met only by geometric model M3. In geometric models M1, M2, M4, and M5, the relative error of measurement was higher, at 21%, 52%, 16%, and 18%, respectively.
2. The volume of cauliflower heads was most accurately determined with the use of geometric model M3. In this model, the relative error of measurement did not exceed 4%. The relative error of volume measurements was higher in geometric models M1, M2, M4, and M5, ranging from 12% to 19%.
3. The smallest average maximum deviation (+) in the dimensions of cauliflower heads was observed in geometric model M3. Cauliflower dimensions determined in model M3 differed from real-world dimensions by 8.03%. The smallest average minimum deviation (-) in the dimensions of cauliflower heads was also noted in model M3, where the modeled dimensions differed from real-world dimensions by 8.33%.
4. The numeric model developed with the use of a 3D scanner can be applied to determine the geometric parameters of whole cauliflower heads and their parts. Numerical 3D models are particularly useful for accurate measurements of surface area, volume, and geometric dimensions. Geometric models can also be applied to determine these parameters, but with smaller accuracy. Since these models describe geometric parameters with lower precision, they can be used in design processes and computer simulations of vegetable processing operations.
5. The presented modeling method supports the generation of relatively accurate 3D models and reliable analyses of the geometric properties of the examined objects. However, the obtained models pose a certain challenge in simulation studies. In simulation studies, complex objects are often modeled

with the use of spheres that offer a simple solution to the problem. These models will be increasingly used in simulations due to rapid advancements in computing power and the introduction of new computational methods.

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