UNIVERSITÀ DEGLI STUDI DI PADOVA
Dipartimento Territorio e Sistemi Agro-forestali
Department of Land, Environment Agriculture and Forestry

Corso di laurea magistrale/Second Cycle Degree (MSc)
in Food and Health

Quantifying Bread Physical Features: A Comparative Analysis Between Standard Method, Structure from Motion, and RGB-D Cameras

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Contents

Abstract

This study aimed to assess the physical attributes of bread by conducting a comparative analysis of three methods: Seed Replacement, Photogrammetry using RGB cameras, and RGB-D cameras. Measurement of bread volume is a crucial parameter in evaluating the quality of baked goods. Conventional methods like Seed Replacement are labor-intensive and may not offer the necessary accuracy for advanced food technology applications. This study investigates the effectiveness and precision of photogrammetry and RGB-D techniques in capturing volumetric data from bread samples. Photogrammetry employed a Canon EOS R10 camera to capture multiple images per sample for creating detailed 3D models, while the RGB-D method utilized depth cameras to generate point clouds and meshes for volume estimation. The results demonstrated a strong correlation between the traditional Seed Replacement method and the advanced RGB-D method, with an R^2 value of 0.9931, signifying high consistency. The photogrammetry method also exhibited a strong correlation with the RGB-D method (R^2 = 0.9925), indicating that both methods can potentially replace traditional techniques reliably. These findings endorse the use of advanced imaging technologies for precise and efficient bread volume measurement, potentially revolutionizing quality control processes in the baking industry.

1. Introduction

1.1. Bread Origine

Bread has been a common food since the Neolithic period and is created by baking dough in an oven. The first bread was made over 12,000 years ago, around 10,000 BC. It is believed that early humans experimented with grain flour and water to develop the recipe. The Egyptians were the first to popularize the art of bread making, which eventually spread throughout the world[1]. For more than two millennia, the production and distribution of bread have been utilized as a means of exercising political power over individuals. To gain a deeper comprehension of the baking process, several experimental and mathematical models have been created. Compared to other common food items, bread is unique because it is a leavened product. It is made by fermenting wheat flour sugars that are released from starch through the action of natural flour enzymes[1].

1.2. Bread Ingredients

For breadmaking, various essential ingredients are needed, with each one serving a critical purpose in the process. The two most important ingredients in any bread recipe are flour and water. These ingredients have a significant impact on the bread's texture and crumb. Flour typically contains 14.5% moisture, and 13% protein, and has a pH of 5.7-6.1[2]. The flour always accounts for 100% of the recipe, while the remaining ingredients are a percentage of that weight. The amount of water used in the recipe affects the final texture of the bread. Light and fluffy bread requires about 50% water, while most artisan bread recipes use anywhere from 60% to 75% water. This creates a coarser breadcrumb with more bubbles of $CO2$[2] In yeast bread, the other ingredients are typically measured based on 100% flour. The recommended amounts are 2% yeast, 4% sugar, 2% salt, and 3% of shortening[2]. Understanding the role of each ingredient in bread-making can significantly impact the overall quality of the final product. This knowledge can influence crucial factors such as the texture, flavor, and volume of the loaf, leading to the production of higher-quality bread.

1.2.1. Flour

The modulation of specific characteristics of bakery products is primarily dependent on flour, making it the most important ingredient in breadmaking. Flour contains protein, starch, carbohydrates, ash, fibers, lipids, water, and tiny amounts of vitamins, minerals, and enzymes[3]. The most utilized type of flour is wheat flour. When wheat is processed into

fermented dough, the resulting loaf of bread is light, delicious, and well-risen. In comparison to other cereal grains, wheat is exceptional due to its ability to produce such desirable qualities in bread when milled into flour[4]. Wheat flour contains two fundamental types of protein: gliadin and glutenin. The behavior of these proteins when separately wetted is completely different. Gliadin creates a sticky and inelastic viscous liquid, while glutenin creates a rubbery material that is more elastic and tenacious[5]. When the two are mixed, known as gluten, and wetted, they form a cohesive and elastic network. This network gives wheat its functional properties. Gluten has been described as the most complex rheological food material known. It is gluten that provides dough with the ability to form thin sheets that can stretch and hold gas[6]

1.2.2. Water

Water plays a crucial role in the formation of dough by providing fluidity. It helps to dissolve salt and sugars and aids in the dispersion of yeast cells. Water also functions as a medium for transporting food to yeast through cell membranes. It is also essential for the hydrolysis of starch and sucrose and is critical for starch gelatinization during baking. Water contributes to the oven spring by vaporization. When water is added to flour, it activates enzymes, promotes the formation of new bonds between macromolecules in the flour, and alters the rheological properties of the dough. The amount of water added depends on the moisture content and physicochemical properties of the flour[7]

1.2.3. Yeast

Saccharomyces cerevisiae is a common yeast used in bread making. Yeast cells process fermentable sugars like glucose, fructose, sucrose, and maltose in the absence of oxygen. This process produces carbon dioxide as a waste product, which helps in leavening the dough and increasing its volume. Yeast also helps in producing gluten network and aromatic compounds[8]. Active yeast is available in two forms: compressed cake and dried. The compressed cake contains around 70% moisture, making it highly perishable unless refrigerated. Active dry yeast is made by extruding cake yeast into fine strands, which are then dried to a low moisture content. The yeast that is instant is derived from yeast strains that are more active and are dehydrated at a quicker rate and to a reduced level of moisture. Active dry yeast has a long shelf-life at room temperature, but it needs to be

hydrated before being added to other ingredients. On the other hand, instant yeast can be directly added to flour and other ingredients without prior hydration[8]

1.2.4. Salt

Salt is essential in the production of baked goods as it serves several important functions. It helps to strengthen gluten, regulate yeast activity, and control the volume of the loaf. A small amount of salt in the dough enhances the flavor and supports the activity of amylase, ensuring a steady supply of maltose for the yeast. In addition, salt inhibits flour proteases, which would otherwise break down the gluten proteins. Dough made without salt may be sticky and challenging to handle.[9]

1.2.5. Sugar

During the initial stages of fermentation, yeast primarily utilizes sugars. Enzymatic activity in the flour subsequently releases additional sugars, which further facilitate gas production. In certain instances, additional sugar may be incorporated to enhance gas production, improve crust coloration, and sweeten the bread. Moreover, sugars function as antiplasticizers, delaying the pasting of native starch, and serve as anti-staling agents by inhibiting starch recrystallization[10]

The fermentation of the carbohydrates by Saccharomyces cerevisiae follows a specific sequence, with a preference for glucose as the primary sugar. The uptake of fructose is inhibited by glucose because both sugars are transported by the same transporters, which have a higher preference for glucose[11]. Yeast's efficient invertase enzyme rapidly converts sucrose into glucose and fructose. When glucose and fructose concentrations are sufficiently high, the maltose level in the dough also rises due to the action of flour's amylase, a starch-degrading enzyme. This enzyme continually produces new glucose and maltose from starch. However, as glucose and fructose are used up, the maltose concentration begins to decline. This decrease presents a challenge for yeast cells to break down maltose promptly, as they lack the necessary enzymatic tools[12]

1.2.6. Lipid

Lipids, whether in the form of fats or oils and commonly known as shortening, are an optional but beneficial ingredient in breadmaking. They enhance dough handling, improve crumb appearance, and contribute to flavor. Moreover, lipids play a key role in improving the bread's softness, moistness, texture, and shelf life. Both endogenous lipids and added fats

are crucial during breadmaking and staling[13] The lipids present in the protein matrix engage with proteins while the dough is being mixed, thereby playing a role in the viscoelastic characteristics of the gluten network that are crucial for the dough to expand and retain gas during proofing. Adding lipids to bread dough results in a larger finished loaf, a softer crust, and an overall improvement in bread quality[14]

1.2.7. Ascorbic Acid

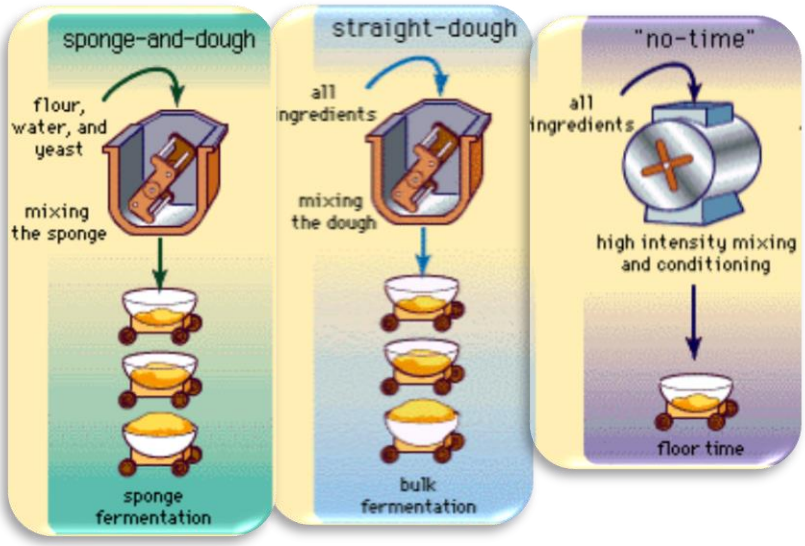
The process of breadmaking relies on oxidation, as adding the right amount of oxidizing agents to flour or dough improves both the handling of the dough and the quality of the bread. During mixing, oxidizing agents convert sulfhydryl (SH) groups of gluten proteins into disulfide (SS) linkages between adjacent molecules, thereby strengthening the gluten matrix and resulting in a more robust dough[14] Ascorbic acid, an important oxidizing agent, plays a significant role in reducing dough stickiness and affecting the structure and interactions of protein molecules. It works by creating disulfide bonds within the gluten network, which decreases the dough's extensibility while increasing its elasticity, ultimately leading to improved dough and bread quality[15]

1.3. Bread Baking Methods

Breadmaking is a temperature-dependent process consisting of two main stages: fermentation and baking. During fermentation, yeast activity produces CO2, which creates a porous dough structure and increases dough volume. In the baking stage, yeast activity ceases, and the bread's structure is solidified[16]. The internal temperature of the bread reaches 100°C. During this stage, gluten cross-links form, and starch granules are disrupted, contributing to the final texture of the bread. The ultimate bread structure is influenced by the composition of the dough ingredients, the activity of the yeast, the temperature during fermentation, and the formation of gas bubbles[17]

There are three primary methods for producing bakery products that utilize yeast as a leavening agent. These methods are commonly used in the production of such goods. In the initial sponge-and-dough method, the mixing of ingredients is carried out in two stages. First, the leavening agent is prepared by mixing yeast, a specific amount of water, and flour, and allowing the mixture to develop for a few hours. In the second stage, the mixture is combined with the rest of the ingredients. The straightforward dough method involves combining all the ingredients in one stage, and the components of the dough may vary

based on the manufacturer's preference and available equipment. In the Chorleywood method, the ingredients are mixed in a high-speed mixer for a short period (Picture 1)[2]



picture 1. Various types of bread-making methods[18]

When the dough is baked correctly, it transforms into bread that boasts exceptional quality and sensory attributes. Usually, fresh bread has a beautiful brownish and crunchy crust, a delightful roasty aroma, the ability to be finely sliced, a soft and elastic texture for the crumb, and a moist mouthfeel[2]. When assessing bread quality, both the volume of the loaf and the texture of the breadcrumb are important factors to consider.

1.4. Factors influencing bread volume

What is bread-specific volume? It is the ratio between total bread volume (cm^3) and mass (g)[19]. The quality of bread is directly proportional to its specific volume, with higher volumes indicating a softer and finer crumb structure.

The bread volume is a reliable indicator of the dough's ability to retain gas, the quality of flour protein, the quality of gluten development, and the alignment of the recipe and processing requirements[20]. Consequently, volume measurement research is an essential endeavor, as factors influencing bread volume are of considerable significance. The following are some key factors that may impact volume:

1.4.1. Protein

One of the factors that have an impact on the bread volume is bread protein however the amount of gliadins and glutenins in bread has a stronger correlation with its volume than the total protein content[21]. Proteins found in flour, such as glutenins, gliadins, albumins, and globulins, which are the main types of wheat proteins, can be separated by their size using high-performance liquid chromatography with size exclusion (SE-HPLC)[22] The gluten network's ability to retain gas throughout fermentation and baking is the primary mechanism that prevents gas bubbles from bursting in bread. The gas retention properties determine the resulting loaf volume and crumb structure[23]

1.4.2. Lipid

The importance of lipids in bread making lies in their functional properties, despite being present in lower quantities compared to starch or protein. Lipids are naturally present in flour or can be added through the use of shortening and/or surfactants. Lipids are present in wheat (Triticum aestivum L.) flour at a level of approximately 2.0-2.5%. The lipid content observed is influenced not only by genetic and environmental factors but also by milling and lipid extraction methods. The end-use quality of flour, particularly the volume of bread loaves, is affected by the composition, extractability, and quantity of lipids in wheat flour. In the initial stages of mixing, a considerable proportion (approximately 70%) of the overall flour lipids bind to or become trapped within the gluten component of the dough[24]. This primarily includes free polar lipids. Various lipid types, such as galactolipids and phospholipids, interact with certain elements of gluten, namely gliadin, and glutenin, through hydrophobic and hydrogen interactions. During the fermentation and proofing processes, carbon dioxide and ethanol are produced by the activity of yeast, causing the expansion of gas cells and an increase in the volume of bread dough. However, in order to obtain an ideal crumb structure, it is crucial to maintain as many gas cells as possible while stabilizing the interface of the gas cells and avoiding coalescence. There are two ways in which they influence this process:

1. Gas Retention: Lipids in wheat flour are known to impact gas retention and foam stability. Shortening, for instance, aids in gas retention by having its lipid crystals adsorbed to the gas cell interface.

2. Stability and Structure: The surfactants present in lipids can impact gas cell stability and contribute to the creation of a stronger gluten network. This stable network is vital for maintaining the structure and volume of the bread during fermentation and baking[24]

1.4.3. Non-endosperm Components

The volume of bread can also be influenced by non-endosperm components. These components include the germ, bran, and epicarp hairs of the wheat caryopsis. Traditional wholemeal bread is often characterized by a dense crumb structure and low specific volume, which is attributed to the presence of these non-endosperm components. However, the exact reason behind the reduction in loaf volume due to their inclusion is not yet understood. Numerous research studies have been conducted to analyze the impact of bran on baking quality[25]. These studies have discovered that the presence of lipid metabolizing enzymes in the bran and germ fractions is the main reason for the decrease in baking performance. Lipase, which is present in the bran, breaks down triacylglycerols, resulting in the accumulation of primarily polyunsaturated fatty acids. When the flour and bran are hydrated, lipoxygenase (present in the germ) oxidizes these fatty acids, leading to poorer baking quality and a decrease in loaf volume. Another chemical component that may cause a decrease in loaf volume is glutathione. This low-molecular-weight tripeptide may lead to a reduction in the cohesive molecular forces within the dough by either catalyzing disulfide interchange or permanent cleavage[25].

1.4.4. Kneading Process

Additionally, the process of kneading plays a vital role in determining the final volume of bread, as it ensures that the dough ingredients are evenly mixed. As the flour constituents are hydrated, a viscoelastic wheat dough structure is formed, which effectively traps air bubbles within the dough matrix. Failure to knead the dough optimally results in gluten structures that are not fully developed, leading to low retention capacity for gas bubbles and ultimately resulting in bread with a hard texture. Conversely, overmixing the dough gradually breaks down the gluten networks, which increases the amount of free water and results in poor-quality bread[26]

1.4.5. Baking Temperature

During the baking process, the volume of bread is affected by the baking temperatures. Research shows that higher temperatures, specifically at 230°C, can result in increased

specific volume and crumb porosity, indicating improved dough expansion and larger loaf volume The influence of temperature goes beyond just direct heat application and affects heat transfer within the oven, moisture diffusion in the dough, and various physical and chemical changes during baking[27] Vault temperature has a significant impact on crust formation, which can limit bread expansion by increasing internal pressure within gas cells and potentially result in reduced loaf volume. Using steam during baking can increase the amount of time that the dough takes to rise, which leads to a better oven spring and prevents the crust from setting too soon. This process ultimately results in bread that is larger in volume[28] In addition, the temperature of the hearth is an important factor in determining the size of gas cells, with smaller cell diameters leading to higher specific volume and porosity. Achieving the optimal balance between temperature, gas dynamics, and crust formation is crucial for achieving the ideal texture and volume of bread. It is crucial to maintain proper temperature control to achieve desired bread characteristics as the correlation between crumb hardness, specific volume, and porosity highlights its importance (Figure 1). Thinner cell walls and uniform gas cell distribution lead to higher specific volumes, resulting in lower crumb hardness. Hence, optimizing bread volume and quality necessitates understanding and manipulating temperature variables[27]

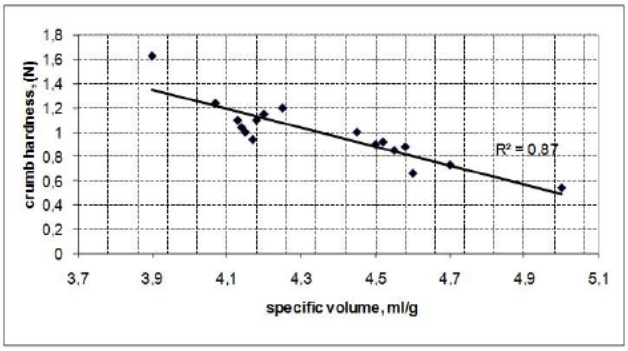


Figure 1 The correlation between the specific volume of bread and the crumb hardness[27]

1.5. Bread Volume measurement method

It is crucial to measure the volume of bread as it is a key factor in evaluating its quality and consistency, which are vital in both commercial production and scientific research. The volume of bread serves as a dependable indicator of the dough's gas retention properties, reflecting the quality of flour protein, gluten development, and overall formulation balance[29]. Furthermore, the specific loaf volume is closely associated with bread-making

quality, encompassing attributes such as dough fermentation and proofing performance[30]. Consequently, bread volume measurement is essential for upholding high standards in bread production and for advancing scientific comprehension of bread-making processes, as well as for customer approval. Different approaches can be employed to measure the size of bread, addressing varied research or industrial requirements. Popular methods comprise rapeseed and water displacement techniques, and laser scanning, coupled with photography and image analysis methods[31]. However, three official methods are usually used: The AACC International Method 10-05.01 is widely recognized as the rapeseed displacement procedure. The AACCI Approved Method 10-14.01 utilizes laser scanning and has been enhanced by the AACC Standard Method 10-16.01, which also encompasses the dimensional profile of the products[31]

1.5.1. Rapeseed And Water Displacement Techniques

The volume of an object is typically measured using the water displacement method, which relies on Archimedes' principle. This method requires immersing the object in water in a container until all surfaces are submerged, and then measuring the volume of the displaced water to determine the object's volume. However, this method is known to be inaccurate, especially when used for porous or fragile objects[32,33]. The water displacement method is unsuitable for measuring bread volume because it can cause damage to the bread by being absorbed. Instead, the seed displacement method is more appropriate for measuring the volume of bread by displacing water. Usually, rapeseed or pearl barley can be utilized as a substitute for water. However, this approach may not be very precise, as the bread could become compacted when it is submerged in the grain[29].

A comprehensive description of the procedure including:

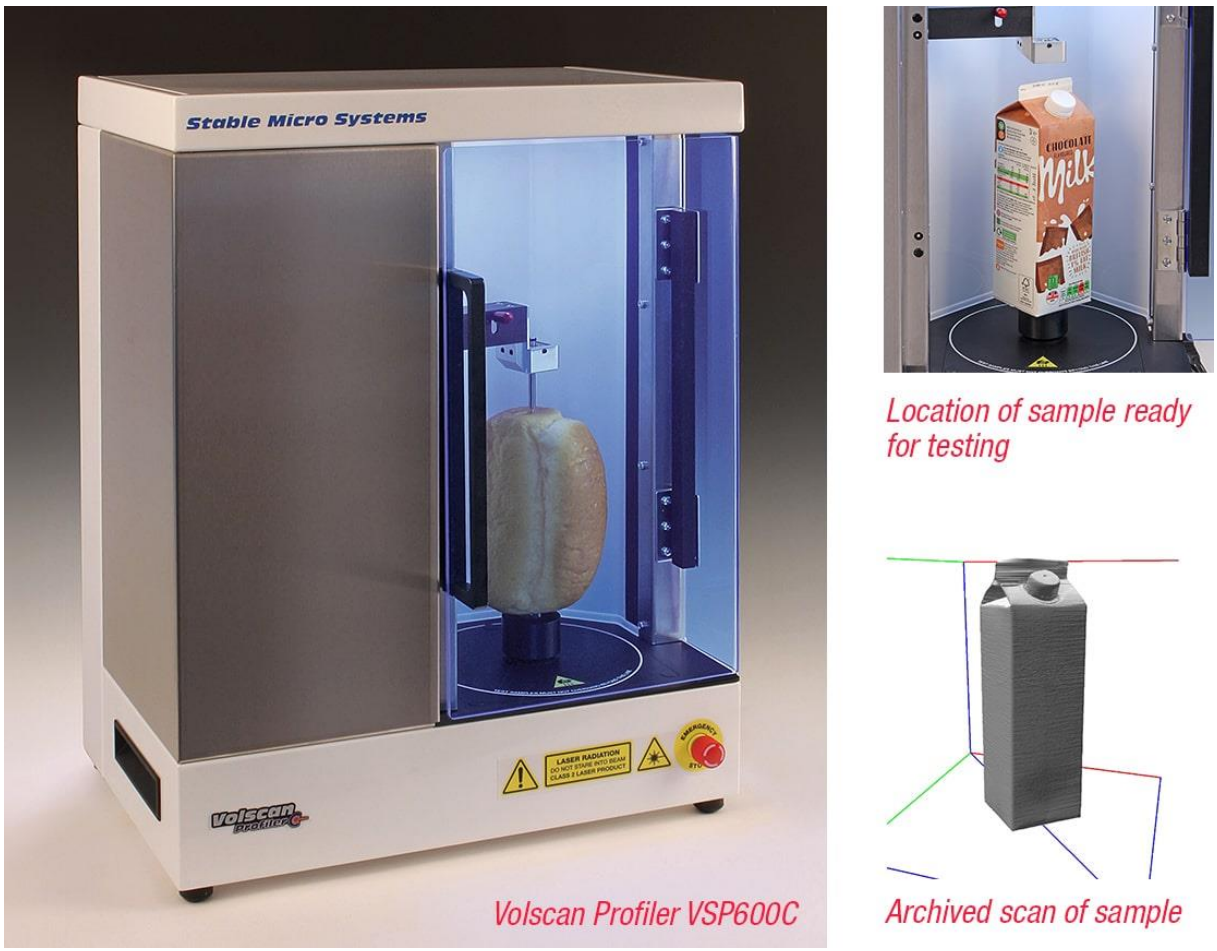
1. **Preparation**: The equipment usually includes a container big enough to accommodate the bread sample and a specific amount of rapeseed. The container needs to be calibrated and equipped with a scale to precisely measure the displaced seed volume.
2. **Initial Filling**: The initial volume is determined by filling the container with rapeseed to a known level and recording it.

3. **Bread Placement**: The sample of bread is placed into the container with great care. It is ensured that the bread is not compressed, as this could impact the precision of the volume measurement.
4. **Displacement Measurement**: The container is filled with rapeseed until it reaches the initial level. The amount of rapeseed needed to restore the container to its initial level is then measured.
5. **Volume Calculation:** The bread's volume is determined by subtracting the initial rapeseed volume from the volume after the bread is added. [31]

picture 2. Seed volumetry method[34]

1.5.2. Laser Scanning

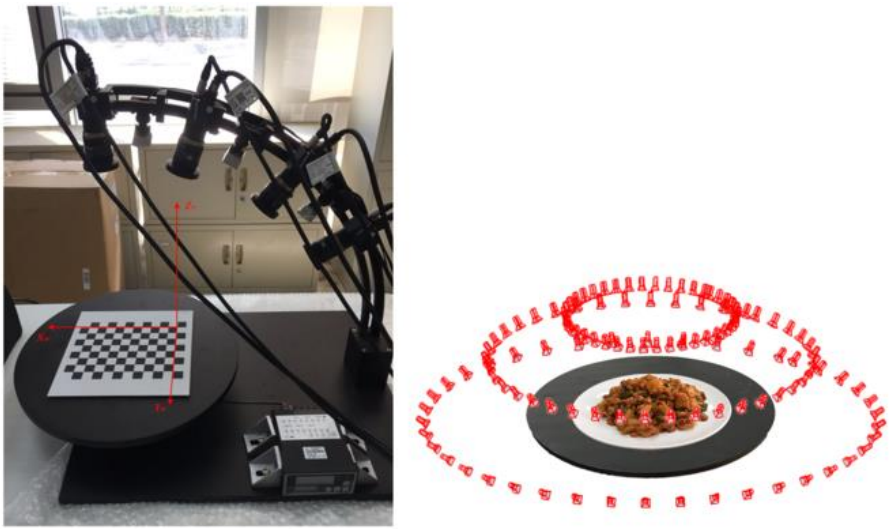
A volume measuring device that utilizes laser scanning technology for food products, particularly bread, has been introduced to the market, including instruments like the TexVol BVM-L series (http://www.texvol.com) and the Volscan Profiler from Stable Micro Systems (http://www.stablemicrosystems.com). However, these instruments are costly and cannot be directly used in a production line. Consequently, a precise and non-destructive method for measuring the volume of food products is necessary[29].



picture 3. The Volscan Profiler[35]

1.5.3. Photogrammetry Method by RGB Camera

Photogrammetry is a method employed to generate an accurate database of a physical object by constructing a digital 3D model using numerous photos captured from various angles around the object. In recent times, various fields, including topography, architecture, engineering, and medicine, have harnessed this technique to create digital 3D models[36].The numerical computation of food volumes can also be achieved by image processing techniques. Food images are typically measured in pixels, which is not a real-world unit like centimeters. Therefore, a scale reference is necessary to estimate the actual size of the food item. To determine the size of an object like an apple, its size must be compared to that of another object in the same image with a known size. This is why several types of fiducial markers, such as a checkerboard, have been used as a scale reference[37] The individual needs to carry these fiducial markers and position them close to the food, which can be a challenging process and is typically not well-received. Secondly, in order to accurately gauge food volumes with the aid of a computer, it is crucial to gather ample three-dimensional (3D) data about the food. Regrettably, a significant portion of this information is forfeited during the imaging phase since food, being a 3D entity, is flattened onto a 2D plane. To address this challenge, numerous researchers have opted to employ multiple images captured from varying angles, rather than relying solely on a single-view image[38,39] Moving either the camera or the food in the imaging process is necessary for this approach, which can complicate the research effort. Furthermore, multi-view image 3D reconstruction poses several challenges, including accurate camera calibration, feature extraction, image registration, pose estimation, etc[40].



Picture4. A platform for acquiring food images[41]

While measuring, the food, whether on a plate or not, is placed on the turntable. The control unit includes a feature for automatically zeroing the weight of the plate to determine the net weight of the food. As the turntable completes a full cycle (360°), a set of cameras captures images simultaneously at various positions (picture 4). The turntable's rotation speed and the positions/angles of the cameras are established, ensuring even distribution of picture-taking points on the food, and minimizing the chance of obstruction. This setup, combined with shadowless illumination from the white LED, results in an imaging platform capable of highly accurate food image reconstruction[41] .

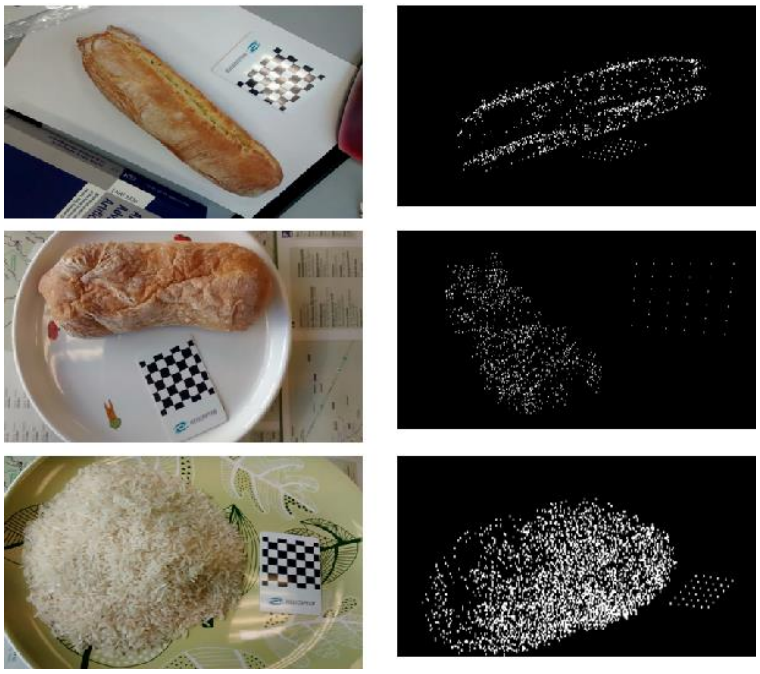
Establishing correspondences between image pixels and real-world coordinates requires calibrating the imaging system. This calibration is a one-time requirement unless the system undergoes readjustment or repositioning. An algorithm is used to perform the calibration, utilizing a checkerboard sheet placed on the turntable. The algorithm section's objective is to create a three-dimensional set of points on the surface of food using two-dimensional images from various angles. Initially, the algorithm automatically selects a set of common points, known as feature points, which are visible in multiple neighboring images. These feature points are then matched one-to-one across as many images as possible. Next, the spatial relationships of these feature points are used to generate a 3D point cloud in real-world units (e.g., millimeters). Finally, any noise-induced outlier points are identified and removed to improve the accuracy of the point cloud[41].

1.5.4. The 3D Reconstruction Based on RGB-D Image

RGB-D images offer an efficient and precise means of building 3D models. Such models can be used to calculate the mass and volume of food. The 3D reconstruction process based on RGB-D images uses depth camera equipment to obtain a direct depth map, which is then processed and fused to create a 3D model of the object. This method is highly accurate, consumes less time, is easy to operate, and is a current research focus in the field of computer vision[42]. Ordinary color cameras record RGB images that store the position and color value of each pixel. The alteration in the Red (R), Green (G), and Blue (B) channels, as well as their combination, represents the color value. Nonetheless, the RGB image does not contain details about the subject's relative position to the camera. Various techniques for reconstructing real-world objects using common color cameras include 3D reconstruction based on deep learning algorithms, monocular vision methods, binocular vision methods, multi-eye vision methods, and more. Deep learning-based 3D reconstruction, in particular, involves using algorithms to infer the 3D structure of the object in an image. However, this method requires extensive training of the model to learn numerous realistic rules, which can be challenging to accomplish[42]

Considerable work has been done to apply computer vision techniques for estimating food volume. Methods can be broadly categorized into two groups: those based on models and those based on stereovision. The volume in mode-based methods is estimated by aligning each food item in the input image with a predetermined 3D model of food. In 2012, Chen et al. conducted research that suggested a method for interactively aligning the food contour and the 2D projection of a manually selected 3D geometric model from a group of computer-generated shapes (such as a sphere, a wedge, or a portion of spheroid) using a 3D/2D model-to-image registration approach[43]This method produces a significant error when the food shape is highly irregular due to the limited set of prescribed 3D shapes. In 2013, Xu et al. proposed a solution by training 3D food representations using multi-view food images. Despite advancements, model-based approaches face a shared issue where a suitable 3D model needs to be chosen manually, impacting data processing speed and cost-effectiveness[44]. Methods utilizing stereovision have been created to tackle this problem, with the goal of reconstructing the three-dimensional surface of food using a sequence of RGB or RGBD images. Puri et al., for instance, devised a reconstruction approach using

multiple images from various perspectives. Likewise, Hassannejad in 2017 produced a point cloud of food by utilizing six consecutive frames from a brief video[45,46].



Picture5. 3D representation of the food item in the shape of a point cloud[46]

Several techniques have been suggested to accelerate the 3D reconstruction process for estimating food volume. A two-view 3D reconstruction algorithm was presented in 2017 as one of these methods. This particular approach utilizes images captured from two distinct perspectives to generate a 3D representation of the food object. Advanced image processing techniques are employed in this method to guarantee precise volume estimation from the reconstructed model[47]. Recently, a new algorithm for Simultaneous Localization and Mapping (SLAM) using a single camera was introduced. This approach enables real-time 3D reconstruction by tracking the camera's position and mapping the environment simultaneously. By combining data from Lidar and monocular vision, the algorithm improves the accuracy of 3D reconstruction, making it more resilient when dealing with different food shapes and sizes[48]. Stereo vision-based methods necessitate less manual effort for volume estimation compared to model-based techniques. Nevertheless, they encounter notable difficulties like image registration, camera calibration, pose estimation, and feature extraction, which complicate their implementation. To perform 3D reconstruction, it is necessary to have several images of the same food item from different angles. This requires moving the camera around the food, which can be challenging with a wearable camera. Although it is feasible to equip a single wearable device with two cameras to capture stereo

images, this will raise the cost and power consumption of the device. Furthermore, the small size of wearable devices may result in a limited distance between the two cameras, which could be insufficient to create a strong enough stereo effect for accurate volume measurement[49] In 2018, Lo and colleagues utilized an RGBD camera to record color and depth images in order to estimate food volume. Their approach entailed reconstructing the food by employing the Iterative Closest Point (ICP) algorithm to align the front-view depth map with an inferred back-view depth map, thereby creating a comprehensive 3D model of the food item[50] Other researchers took a different approach by formulating volume estimation as a regression issue. They converted implicit 3D features obtained from depth information into volume estimates, thereby avoiding the requirement for explicit 3D reconstruction. This technique utilizes deep learning to analyze depth data and accurately estimate food volume[51]

Despite recent advancements in image-based food volume estimation, many methods still encounter several challenges: (1) they require a lot of human effort to choose and handle 3D food models; (2) they necessitate specialized equipment such as an RGBD camera, multiple RGB cameras, or moving a single RGB camera around the food during image capture; and (3) they rely heavily on estimated depth information, which is often limited in single-view or restricted-view images, leading to significant errors and instability in the results[49]

2. Material and Method

The research was carried out in the laboratory at the Agripolis campus of the University of Padova (UNIPD), commencing on June 15, 2024. Twenty bread samples of different sizes were examined using three distinct volume measurement techniques. The initial approach involved the standard seed replacement method, followed by volumetry using photogrammetry by RGB imaging, and lastly, RGBD imaging. Each method was applied to the bread samples to assess their efficiency and accuracy in measuring bread volume.

2.1. Seed replacement

2.1.1. Seed replacement material:

1. Bread Samples: Twenty distinct types of bread were used for volume evaluation.
2. Containers: Three different containers
3. Seed: Trifolium Repens seeds commonly known as White Clover
4. Water: To determine the volume of the containers
5. Precision Scale: The scale used is precise to 0.1 grams, with a maximum weight capacity of 6000 grams and a minimum measurable weight of 2 grams

2.1.2. Seed replacement method:

Bread measurement: Scale the weight of the bread.

Container Volume Measurement: Fill up each container with water until it reaches full capacity and then measure the amount of water used to fill each container in order to determine its volume.

Seed Measurement without Bread: Pour the seeds into the container, ensuring that the seeds completely fill the container and flatten the surface. Use the tared container weight to measure the weight of the seeds in the container.

Seed Measurement with Bread: Put the bread sample into the container. Fill up the rest of the container with the Trifolium Repens seeds, making sure the seeds completely fill the container and the surface is leveled. Weigh the total amount of seeds and bread in the container, with the weight of the empty container subtracted.

Volume Calculation: To calculate the bulk density of the seeds, divide the weight of the seeds that filled the container by the volume of the container. Then, when calculating the combined weight of the bread and seeds, subtract the weight of the bread from the total

weight to find the weight of the seeds. The volume can be calculated by dividing the weight of the seeds used by the seed bulk density. Finally, the volume of the bread can be found by subtracting the volume of the seeds from the total volume of the container.

2.2. Photogrammetry, RGB-360

2.2.1. Photogrammetry material:

1. Bread Samples: Ten distinct types of bread were used for volume evaluation.
2. RGB Camera: A Canon EOS R10 camera mounted on a rotating holder.
3. Projectors: A pair of projectors positioned on an identical rotating mount to eliminate any shadows
4. Holder: A hard plastic holder that rotates and moves 360 degrees around the bread sample
5. Hanging Cube: A wooden cube from which the bread sample is suspended.
6. Photogrammetry Software: A program employed for manipulating images and generating a three-dimensional representation of the bread.
7. Photogrammetry Indicators: Markers attached to the wooden cube to aid in the 3D reconstruction process.

2.2.2. Photogrammetry method:

Setup: Place the camera and two projectors on the rotating holder. The camera parameters are listed in Table 1. To ensure accuracy, manual focus was used to avoid errors that can occur with auto-focus. Make sure the two projectors are placed in a way that avoids shadows in the captured images, with one above the camera and the other below. Adjust the position of the projectors manually each time to minimize the shadows and find the best positions. To ensure high-quality results during processing, it is important to use diffused lighting to prevent harsh shadows, as these shadows can result in holes in the final point cloud[36]. Suspend the bread sample from a wooden cube with photogrammetry indicators attached to it.

Camera	Canon EOS R10
Sensor size	22.3mm x 14.9mm (APS-C)
Pixel size (mm)	3.7
Image resolution	6000 x 4000
Autofocus	No (Manual Focus)
Output format	JPEG, RAW

Table1. Basic parameters of the camera

Image Capture: The Holder Moves the camera in a full circle around the bread sample (360 degrees). While completing each full circle, the camera should take 45 photographs of the bread sample, with a photo being taken every two seconds. This means that it takes 90 seconds to capture all 45 photos during one full circle. Repeat the process of capturing images from three different perspectives: one set with the camera positioned directly facing the sample, and two sets with the camera tilted at an angle of about 45 degrees to the sample (one set with the camera positioned above the sample and one set with the camera positioned below the sample). A total of 135 images are captured for each bread sample (45 images per angle x 3 angles).

3D Model Reconstruction: Import the 135 images into the Agisoft Metashape Software. Agisoft Metashape stands as a standalone software tool that conducts photogrammetric processing of digital images and produces 3D spatial data for utilization in GIS applications, documenting cultural heritage, and creating visual effects. Additionally, it facilitates the indirect measurement of objects across different scales. The software operates in a semi-automated manner, and the Workflow sequence and settings are shown in Figure 2. The photogrammetry indicators on the wooden cube assist in accurately aligning the images to form the 3D model[52].

Volume Calculation: The first step includes aligning photos to generate a point cloud by automatically identifying and aligning the 3D location of important feature points in two or more images. The database of the extracted features is then used to determine the position and calibration parameters of the camera. Subsequently, the detected markers and identified Indicators are utilized to transfer real dimensions to the resulting 3D model. The second stage of processing includes generating dense point clouds by integrating the camera positions and feature points. Finally, the 3D mesh of the object and its texture is produced[36]. The software allows for the calculation of the volume and surface area of each sample.

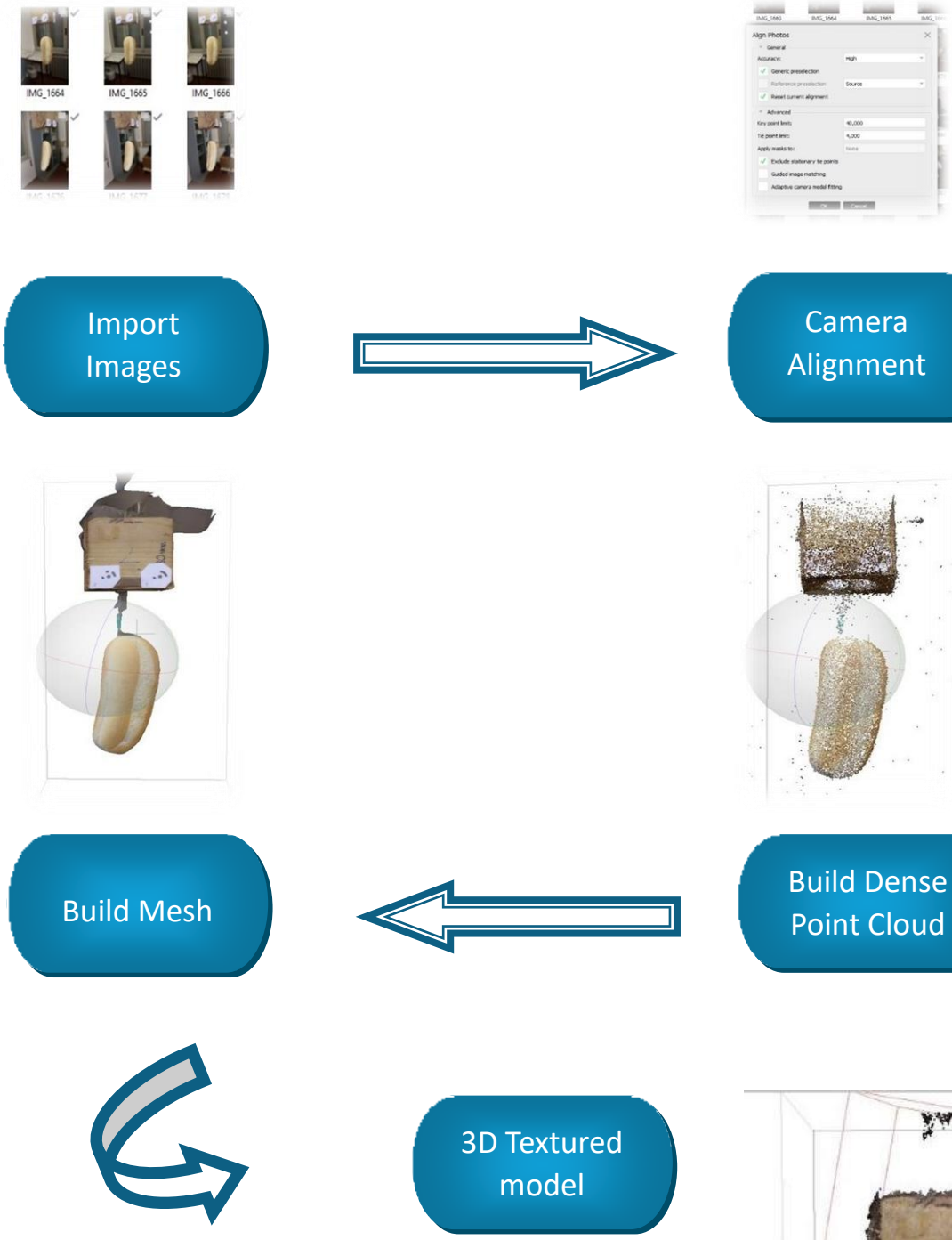


Figure2. Agisoft Metashape workflow used for 3D model generation

2.3.RGB-D

2.3.1.RGB-D Material:

1. Bread Samples: Twenty distinct types of bread were used for volume evaluation.
2. RGB-D Cameras: Cameras that are capable of capturing both color (RGB) and depth (D) information.
3. Cloud Compare Software: Software utilized for generating point clouds and calculating volume and surface area.
4. MeshLab Software: Software used to close holes in the mesh generated from the point cloud.

2.3.2.RGB-D method:

Image Capture: Capture images of the bread samples using RGBD cameras. Make sure the cameras are positioned to capture detailed color and depth information for each sample. Make sure to align the camera at a precise 90-degree angle to the samples and capture three images of each sample from three different perspectives of bread. During the scanning process, the depth image may lose important details due to the influence of the surrounding environment. Therefore, it is essential to apply filtering to the input data's depth image in order to minimize noise[42].

Point Cloud Generation: Import the images that were taken into the CloudCompare software. Generate a point cloud for every bread sample by utilizing the RGB and depth information from the images.

Mesh Creation: Convert the point cloud into a mesh using CloudCompare software. Ensure that the mesh accurately represents the surface topology of the bread sample.

Hole Closing: Import the mesh into the MeshLab software. Utilize MeshLab to seal any gaps in the mesh that might have occurred due to incomplete data capture or processing errors. Verify the solidity of the mesh by identifying and fixing any openings or irregularities.

Volume and Surface Area Calculation: Re-import the completed mesh into CloudCompare software. Use CloudCompare to calculate the volume and surface area of the bread sample from the finalized mesh.

3. Results

3.1. Seed replacement

The experiment aimed to measure the volume of bread samples using the seed replacement method, which is a commonly used technique for measuring irregular objects. Twenty samples of bread with different shapes were utilized to conduct a thorough analysis. These samples accurately represented various types and forms of bread, offering a wide-ranging dataset for measuring volume (picture 6).

Picture6. Twenty bread samples were used for volumetry.

In the course of our experiments, we assessed a total of 20 samples using Trifolium Repens seeds in three different types of containers. The first two containers were constructed from plastic and were chosen for their wide cross-sectional area, allowing for the horizontal accommodation of bread sizes ranging from 8 cm to 29 cm in height. However, we observed that the slight flexibility and generous opening of these containers impacted the accuracy of seed filling. To address this issue, we opted for a third container made of hard plastic with a narrower opening. This specific choice was made for its robust construction and stability, which ultimately minimized variations in seed displacement and improved the precision of

the experimental results. The hard plastic container required the bread to be placed in a vertical position, resulting in reduced errors (picture 7)

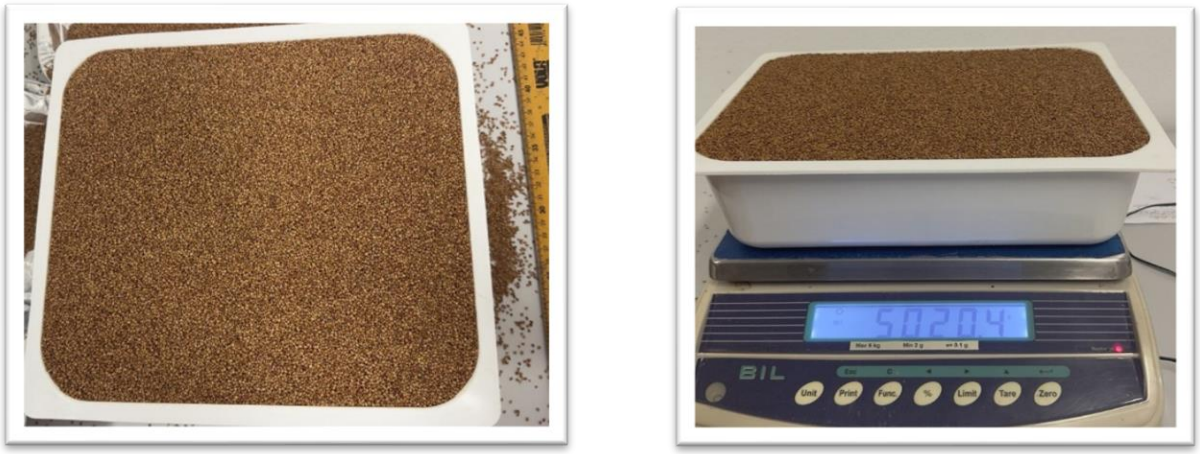
Picture 7. Three containers utilized in the seed replacement method

The first step of this process involves weighing each empty container with the scale. Next, the volume of the container is measured by filling it with water and recording the volume of water required to fill it, making sure the surface is level. The volume measurement is then documented (Table 2).

Container	Weight (g)	Volume (cm^3)
First	120.1	6000
Second	182.5	4800
Third	1018	5900

Table 2. weight and volume of three containers.

The container underwent an initial calibration using seeds to establish a baseline volume measurement. This involved filling each container with seeds, leveling the surface, and recording the weight (Picture 8). Plastic containers were used for the initial measurements, with the second one being less flexible compared to the first, and the last one being made of hard plastic. Each container was filled with a bread sample, and seeds were added until the container was full. Following this, the weight of the bread and the combined weight of the bread and seeds were recorded after leveling out the contents (Tables 3,4,5).



Picture8. Calibration step using container and seeds.

samples	Seed Weight for Calibration (g)	Bread Weight (g)	Total Weight (g) (Bread + Seed)	Seed Used (g) (Total Weight - Bread Weight)
1	5020.4	42.8	4760.9	4598
2	5034.4	60.9	4708.7	4527.7
3	4939.6	73.7	4653.3	4459.5
4		76.6	4592.2	4395.5
5		125.6	4521.9	4276.2
6		166.8	4500.9	4214
7		317.2	4091.8	3654.5
8		60.1	4710.7	4530.5
9		38.7	4759.6	4600.8
10		166.9	4448.3	4161.3

Table 3. Seed replacement method analysis of the Initial 10 Bread Samples with the first container

samples	Seed Weight for Calibration (g)	Bread Weight (g)	Total Weight (g) (Bread + Seed)	Seed Used (g) (Total Weight - Bread Weight)
1	3935.8	36.9	3761.3	3724.4
2	3876.7	46.6	3722.1	3675.5
3	3910.1	54.7	3726.3	3671.6
4		66.6	3603.1	3536.5
5		96.5	3636.6	3540.1
6		133.3	3561	3427.7
7		253.6	3249	2995.4
8		51.2	3771.6	3720.4
9		31.8	3749.2	3717.4
10		127.7	3539	3411.3

Table 4. Seed replacement method analysis of the Initial 10 Bread Samples with the second container

samples	Seed Weight for Calibration (g)	Bread Weight (g)	Total Weight (g) (Bread + Seed)	Seed Used (g) (Total Weight - Bread Weight)
1	4529.20	36.60	4463.40	4426.80
2	4541.00	46.70	4434.50	4387.80
3	4552.80	54.70	4401.70	4347.00
4		66.80	4287.90	4221.10
5		96.30	4293.90	4197.60
6		132.80	4291.80	4159.00
7		250.30	3983.30	3733.00
8		51.00	4450.30	4399.30
9		31.80	4465.10	4433.30
10		127.80	4232.90	4105.10
11		70.01	4269.40	4199.39
12		33.60	4452.90	4419.30
13		61.40	4309.40	4248.00
14		32.40	4430.10	4397.70
15		77.50	4304.20	4226.70
16		67.60	4373.60	4306.00
17		78.40	4317.10	4238.70
18		41.80	4455.40	4413.60
19		89.80	4276.40	4186.60
20		54.90	4378.30	4323.40

Table 5. Seed replacement method analysis of the 20 Bread Samples with the third container

In the presented tables, it is clear that the weights of the initial 10 bread samples exhibit variations in different trials. These differences are attributable to the measurements being conducted on different days, which leads to disparities in the evaporation of water from the bread. As water evaporates, the volume of the bread reduces, resulting in a decrease in weight. Despite these discrepancies, the weight of the bread was consistently recorded for each trial, ensuring the accurate collection and analysis of data.

Based on the data presented in Tables 3,4, and 5, the volumes obtained from the hard plastic container were compared to those from the plastic containers. It was found that the hard plastic container consistently provided the most accurate and reliable measurements, confirming its suitability for this method. Each container was covered with seeds, and their weight was measured three times. The hard plastic container with a narrower opening consistently yielded remarkably close weights, indicating high reliability. In contrast, the measurements from the two plastic containers were inconsistent and not as close, rendering them unsuitable for precise volume calculations. Therefore, we have decided to proceed with the hard plastic container.

Upon completing the calibration and measurement of each bread and seed weight, it is necessary to determine the seed bulk density. The formula to calculate the bulk density (γ) of the seeds is as follows:

$$\gamma = \frac{m}{v}$$

where:

- m is the mass of the seeds that completely fill the container.
- v is the volume of the container.

Consequently, we will be able to compute the volume of seeds utilized in each bread and seed experiment using the equation:

$$V\ seeds = \frac{m\ seeds}{\gamma}$$

where:

- $\mathrm{m\ seeds}$ is the mass of the seeds used in each experiment.
- γ is the bulk density of the seeds.

Finally, the volume of the bread $(\mathrm{V\ Bread})$ can be calculated by subtracting the volume of the seeds from the total volume of the container:

$$Vbread = V\ container - V\ seed$$

Samples	Container weight(g)	Seed Average weight for calibration(g)	bread weight (g)	*Total Weight (g) (Bread + Seed)*	Seed Used (g) (Total Weight - Bread Weight)	seed bulk density (g/cm3)	seed volume (cm3)	Bread volume (cm3)
1	5900	4541.00	36.60	4463.40	4426.80	0.77	5751.62	148.38
2			46.70	4434.50	4387.80		5700.95	199.05
3			54.70	4401.70	4347.00		5647.94	252.06
4			66.80	4287.90	4221.10		5484.36	415.64
5			96.30	4293.90	4197.60		5453.83	446.17
6			132.80	4291.80	4159.00		5403.68	496.32
7			250.30	3983.30	3733.00		4850.19	1049.81
8			51.00	4450.30	4399.30		5715.89	184.11
9			31.80	4465.10	4433.30		5760.07	139.93
10			127.80	4232.90	4105.10		5333.65	566.35
11			70.01	4269.40	4199.39		5456.16	443.84
12			33.60	4452.90	4419.30		5741.88	158.12
13			61.40	4309.40	4248.00		5519.31	380.69
14			32.40	4430.10	4397.70		5713.81	186.19
15			77.50	4304.20	4226.70		5491.64	408.36
16			67.60	4373.60	4306.00		5594.67	305.33
17			78.40	4317.10	4238.70		5507.23	392.77
18			41.80	4455.40	4413.60		5734.47	165.53
19			89.80	4276.40	4186.60		5439.54	460.46
20			54.90	4378.30	4323.40		5617.28	282.72

Table 6.Analysis of the seed replacement method for 20 bread samples using the third container, along with the measurements of seed bulk density and bread volume.

3.2. Photogrammetry, RGB-360

In this method, we used the Canon EOS R10 camera and photogrammetry approach to quantify the volume of the first 10 bread samples. An RGB camera was mounted on a rotating stand, taking 45 photos in a full 360-degree rotation, with one photo captured every 2 seconds (picture 9). Images were captured of every bread sample from three different perspectives: straight on, at a 45-degree angle from above, and a 45-degree angle from below, resulting in a total of 135 images per sample. In addition, two lights were affixed to the holder to minimize shadows during image capture, thereby improving the accuracy of the resultant 3D models. All captured images were processed using Agisoft Metashape Software to generate 3D models for each bread sample. Four indicators were affixed to the cube positioned above the samples, and their precise distances were measured. These indicators and their measurements were utilized as a reference in the Agisoft Metashape Software. Subsequently, the software generated detailed 3D images complete with texture, enabling calculations of the volume and surface area of each bread sample (Table 7).

Picture9. RGB-360 method for bread volumetry

SAMPLE	Surface (cm^2)	Volume (cm^3)
1	174.4	178
2	237.56	232
3	274.92	300
4	338.37	422
5	410.87	534
6	532.41	545
7	681.41	1258
8	207.62	215
9	166.84	176
10	465.81	650

Table 7: Initial 10 bread samples volume and surface area measured by photogrammetry method

3.3.RGB-D

The RGB-D method employs a depth camera to capture detailed images of the samples. This process involves the use of two software applications: CloudCompare and MeshLab. First, we obtained point cloud data of the bread samples by capturing three images from three different sides of each bread using the depth camera. This data was then imported into CloudCompare for processing (Picture 10). In CloudCompare, we generated a mesh from the point cloud data; however, this initial mesh may contain holes due to noise or incomplete coverage of the bread's surface. To address these issues, we used MeshLab to close the holes in the mesh. MeshLab offers robust tools for repairing and refining meshes, ensuring a complete and accurate representation of the bread samples. Once the holes in the mesh were covered, we returned to CloudCompare to perform volume and surface area calculations (Picture 11). CloudCompare allowed us to obtain volume and surface area data for our samples by providing measurements from the complete mesh (Table 8).

Picture 10: Point cloud generated by RGB-D camera

Picture11: A green mesh displays a mesh with the hole and a blue mesh shows the same mesh with the holes covered in MeshLab software

Sample	Surface (cm^2)	Volume (cm^3)
1	177.942	163.92
2	268.065	226.78
3	271.1	268.71
4	352.401	418.55
5	482.935	478.54
6	631.684	575.76
7	705.979	1144.75
8	253.282	221.16
9	185.111	165.19
10	535.519	620.69
11	393.753	475.45
12	189.418	182.85
13	306.22	374.30
14	186.075	178.30
15	403.881	434.97
16	278.48	335.04
17	318.294	395.02
18	186.467	167.32
19	401.001	490.13
20	261.739	286.99

Table8. The volume and surface area of each loaf of bread were determined using the RGB-D method.

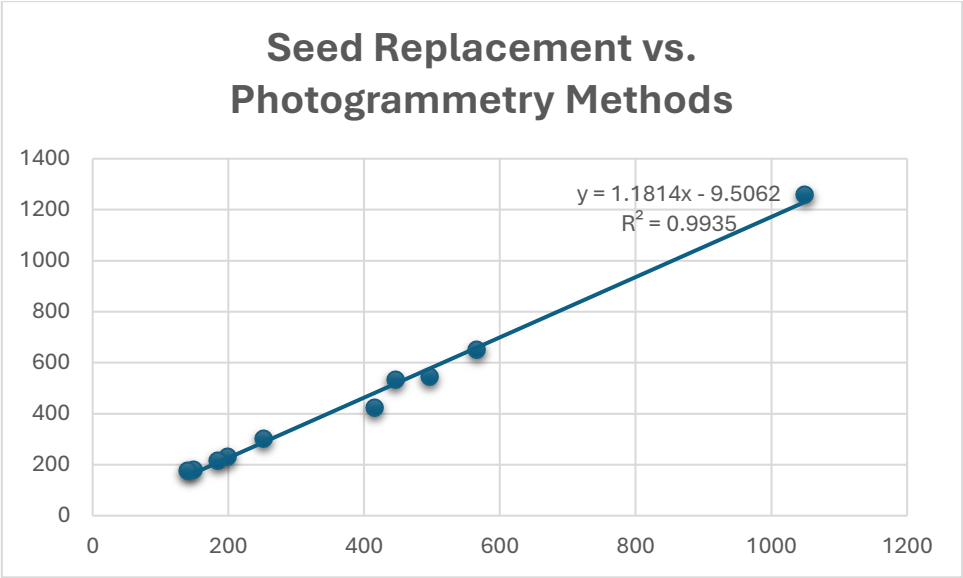


Figure 3. Correlation analysis of seed replacement and photogrammetry volumetry method for the initial 10 bread samples.

This chart (Figure 3) displays the correlation between volumetric measurements of 10 initial bread samples using two different methods: the Seed Replacement method and the Photogrammetry method. The horizontal axis (x) represents the volumetric measurements obtained via the Seed Replacement method, while the vertical axis (Y) represents the measurements obtained using the Photogrammetry method. The scatter plot illustrates a strong positive linear correlation between the two methods, with an R^2 value of 0.9935, indicating high consistency in volumetric measurements across both methods.

The blue dashed line represents the line of best fit, described by the equation $y=1.1814x-9.5062$. This equation reveals that the Photogrammetry method's measurements tend to be slightly higher than those of the Seed Replacement method on average. The data points closely align with the regression line, further demonstrating the accuracy and agreement between the two methods.

In summary, the chart effectively shows that the Photogrammetry method can reliably replicate the volumetric results obtained by the Seed Replacement method, suggesting that Photogrammetry is a viable alternative for the volumetric analysis of bread samples.

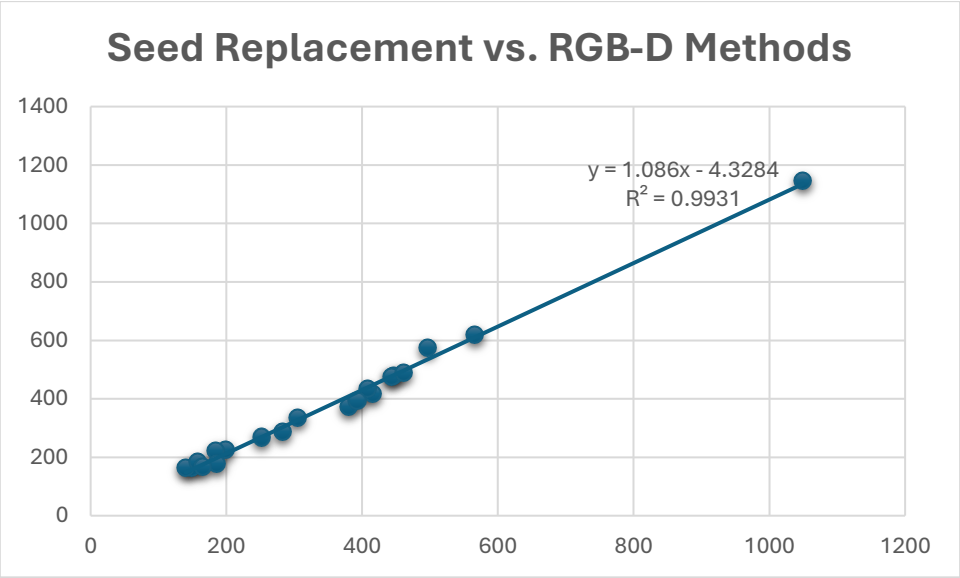


Figure 4. Correlation analysis of seed replacement and RGB-D volumetry method for the 20 bread samples.

This chart (Figure 4) presents a comparative analysis of volumetric measurements of 20 bread samples using two different methods: the Seed Replacement method and the RGB-D method. The horizontal axis (x) represents the volumetric measurements obtained via the Seed Replacement method, while the vertical axis (Y) represents the measurements obtained using the RGB-D method. The scatter plot indicates a strong positive linear correlation between the two methods, as evidenced by the R^2 value of 0.9931. This suggests that the volumetric measurements from both methods are highly consistent with each other.

The blue dashed line represents the line of best fit, described by the equation $y=1.086x-4.3284$. This equation shows that the RGB-D method's measurements tend to be slightly higher than those of the Seed Replacement method on average. The closeness of data points to the regression line further indicates a high degree of accuracy and agreement between the two volumetric measurement methods.

Overall, the chart effectively demonstrates that the RGB-D method can reliably replicate the volumetric results obtained by the Seed Replacement method, making it a potentially viable alternative for volumetric analysis in similar contexts.

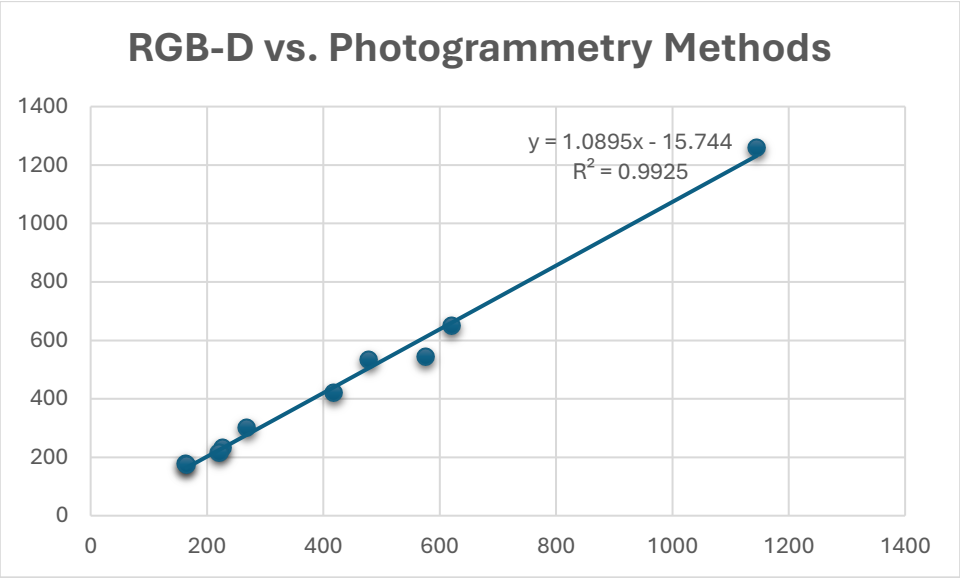


Figure 5. Correlation analysis of RGB-D and photogrammetry volumetry method for the initial 10 bread samples.

The graph (Figure 5) illustrates the relationship between volumetric measurements obtained using RGB-D methods and photogrammetry methods for the first 10 initial bread samples. Each data point on the graph represents a pair of measurements from these two methods, plotted with circles. The best-fit line, described by the equation $y=1.0895x-15.744$ and an R^2 value of 0.9925, indicates a strong linear correlation between the RGB-D and photogrammetry measurements. The slope of the line (1.0895) suggests that the photogrammetry method tends to measure slightly higher volumes than the RGB-D method, with a minor negative offset represented by the y-intercept (-15.744). The high R^2 value (0.9925) signifies that the volumetric measurements from both methods are closely aligned, suggesting that either method can be used interchangeably for assessing the volume of bread samples. Adjustments might be needed to account for the small systematic differences indicated by the regression equation, but overall, both methods provide comparable and reliable volumetric data.

4. Discussion

The main objective of this study was to assess the accuracy and precision of photogrammetry and RGB-D camera techniques in measuring bread volume compared to the Standard Seed Replacement method. The findings demonstrated that both advanced imaging methods yield dependable and precise volumetric results.

In the case of photogrammetry, which utilized a Canon EOS R10 camera, the process involved capturing multiple images from various perspectives to create detailed 3D models of the bread samples. This method proved to be effective, providing highly accurate measurements of volume and surface area. The resulting 3D models allowed for meticulous calculations, establishing photogrammetry as a robust approach for estimating bread volume. However, it should be noted that this method demands substantial computational resources and time for image processing and model generation.

RGB images captured by standard color cameras are able to record the position and color values of each pixel. The color values are represented by the variations in the Red (R), Green (G), and Blue (B) channels. However, these images do not contain information about the relative positioning between the subject and the camera. Various 3D reconstruction methods using regular color cameras consist of deep learning algorithms, monocular vision, binocular vision, and multi-eye vision. Deep learning-based 3D reconstruction involves inferring the 3D structure from images by training models on extensive data, which can be quite challenging. Monocular vision-based reconstruction requires changing the relative position of the object and camera to calculate depth through movement-generated disparity, but it is limited by scale uncertainty. Binocular vision-based reconstruction uses two cameras with fixed relative positions to estimate pixel depth through disparity and baseline, but it requires complex setup and calibration, and its accuracy is limited by the baseline and resolution of the cameras. Additionally, smooth or untextured surfaces pose matching difficulties.

The RGB-D method utilizes depth cameras to capture RGB images along with depth data, offering a different approach. Depth cameras use methods like structured light and Time of Flight (ToF) to gather depth data, resulting in range images that provide distance information for all points on the target object. Every pixel in an RGB image corresponds to a depth image

pixel, enabling the determination of each point's position in the 3D coordinate system. This method simplifies the process of obtaining volumetric measurements by directly creating point clouds and meshes, which are then processed to calculate the volume of the object. The RGB-D method demonstrated a strong linear correlation with the Seed Replacement method ($R^2 = 0.9931$) and photogrammetry ($R^2 = 0.9925$), indicating its reliability and potential as a practical alternative.

The comparative analysis showed that the measurements obtained through the RGB-D method tended to be slightly higher than those obtained through Seed Replacement. This was indicated by the regression equation $y = 1.086x - 4.3284$. Similarly, photogrammetry measurements also displayed a slight positive bias compared to RGB-D, with the regression equation $y = 1.0895x - 15.744$. These differences emphasize the importance of calibration and adjustment when switching between methods to ensure consistent results.

The study highlights the benefits of utilizing advanced imaging technologies for measuring bread volume. Both photogrammetry and RGB-D methods yield precise, consistent, and reproducible results, improving the accuracy of quality assessments in the baking industry. Future research could concentrate on refining these methods for quicker processing and integrating them into automated quality control systems. This development would not only enhance efficiency but also offer more comprehensive insights into the physical attributes of baked goods, contributing to better product development and quality assurance.

By embracing these advanced techniques, the baking industry can establish more precise and efficient quality control, ultimately resulting in higher-quality products and enhanced consumer satisfaction. The shift from traditional to modern methods represents a significant advancement in food technology, promising increased precision and reliability in product evaluation.

5. Conclusion

This study successfully demonstrated the efficacy of imaging technologies, specifically photogrammetry and RGB-D methods, for measuring the volumetric attributes of bread. Both methods exhibited high levels of accuracy and reliability, as evidenced by their strong correlations with the standard Seed Replacement method. Photogrammetry showed a correlation coefficient (R^2) of 0.9925 with the Seed Replacement method, while the RGB-D method showed an even higher correlation ($R^2 = 0.9931$). Despite slight variances, the RGB-D method tended to yield marginally higher volume measurements compared to the Seed Replacement method, as indicated by the regression equation $y = 1.086x - 4.3284$. Similarly, the photogrammetry method exhibited a slight positive bias relative to the RGB-D method, with a regression equation of $y = 1.0895x - 15.744$.

These findings underscore the potential of photogrammetry and RGB-D technologies to enhance quality control processes in the baking industry. By offering precise, consistent, and reproducible volumetric measurements, these advanced methods can significantly improve the accuracy of quality assessments, thereby supporting more stringent product development and quality assurance protocols. Future research should explore the broader application of these technologies across different types of baked goods and other food products to further validate their utility and versatility.

In brief, the integration of photogrammetry and RGB-D methods represents a substantial advancement in the realm of food technology, offering a robust substitute for traditional volumetric measurement techniques. This innovation could potentially transform quality control practices in the baking industry, ensuring elevated standards of product uniformity and quality.

References

1. Mondal, A. & Datta, A. K. Bread baking - A review. *Journal of Food Engineering* vol. 86 465–474 Preprint at https://doi.org/10.1016/j.jfoodeng.2007.11.014 (2008).

2. Giannou, V., Kessoglou, V. & Tzia, C. Quality and safety characteristics of bread made from frozen dough. *Trends Food Sci Technol* **14**, 99–108 (2003).

3. Charley, H. & Weaver, C. (1998). Foods–A scientific... - Google Scholar. https://scholar.google.com/scholar?q=Charley%2C%20H.%20%26%20Weaver%2C%20C.%20(1998).%20Foods%E2%80%93A%20scientific%20approach%20(pp.%20164%E2%80%93167%2C%20202%E2%80%93205%2C%20224%E2%80%93225).%20Prentice-Hall.

4. Bushuk, W. & Rasper, V. *Wheat: Production, Properties and Quality*. (1994).

5. Singh, H. & MacRitchie, F. Application of Polymer Science to Properties of Gluten. *J Cereal Sci* **33**, 231–243 (2001).

6. Bushuk, Walter., Rasper, V. F. & World Congress of Food Science and Technology (8th : 1992 : Toronto, Ont.). Wheat : production, properties and quality. 239 (1994).

7. Gil, M. J., Callejo, M. J. & Rodríguez, G. Effect of water content and storage time on white pan bread quality: instrumental evaluation. *Zeitschrift für Lebensmitteluntersuchung und -Forschung A* **205**, 268–273 (1997).

8. Charley, H. & Weaver, C. (1998). Foods–A scientific... - Google Scholar. https://scholar.google.com/scholar?q=Charley%2C%20H.%20%26%20Weaver%2C%20C.%20(1998).%20Foods%E2%80%93A%20scientific%20approach%20(pp.%20164%E2%80%93167%2C%20202%E2%80%93205%2C%20224%E2%80%93225).%20Prentice-Hall.

9. Wood, B. *Microbiology of Fermented Foods*. (2012).

10. Faridi, H. & Faubion, J. *Dough Rheology and Baked Product Texture*. (2012).

11. Bryan, A., Hart, C., Wise, M. & Roberts*, B. Glucose Concentrations Effect on Rate of Fermentation in Yeast. *Journal of Undergraduate Biology Laboratory Investigations* **1**, (2018).

12. Sasano, Y. *et al.* Overexpression of the yeast transcription activator Msn2 confers furfural resistance and increases the initial fermentation rate in ethanol production. *J Biosci Bioeng* **113**, 451–455 (2012).

13. Collar, C., Armero, E., Lebensmitteluntersuchung, J. M.-Z. für & 1998, undefined. Lipid binding of formula bread doughs Relationships with dough and bread technological performance: Relationships with dough and bread technological. *SpringerC Collar, E Armero, J MartinezZeitschrift für Lebensmitteluntersuchung und-Forschung A, 1998•Springer* **207**, 110–121 (1998).

14. Demiralp, H., Celik, S., and, H. K.-E. F. R. & 2000, undefined. Effects of oxidizing agents and defatting on the electrophoretic patterns of flour proteins during dough mixing. *SpringerH Demiralp, S Celik, H KökselEuropean Food Research and Technology, 2000•Springer*.

15. Rouille, J., Bail, A. Le, engineering, P. C.-J. of food & 2000, undefined. Influence of formulation and mixing conditions on breadmaking qualities of French frozen dough. *ElsevierJ Rouille, A Le Bail, P CourcouxJournal of food engineering, 2000•Elsevier*.

16. Shehzad, A. *et al.* Porosity and stability of bread dough during proofing determined by video image analysis for different compositions and mixing conditions. *Food Research International* **43**, 1999–2005 (2010).

17. Shehzad, A., Khan, M. R. & Shabbir, M. A. Yeast, its types and role in fermentation during bread making process-A review. (203AD).

18. Baking - Sweet Breads | Britannica. https://www.britannica.com/topic/baking/Sweet-breads.

19. Mudgil, D., Barak, S. & Khatkar, B. S. Optimization of bread firmness, specific loaf volume and sensory acceptability of bread with soluble fiber and different water levels. *J Cereal Sci* **70**, 186–191 (2016).

20. Sahi, S. S., Little, K. & Ananingsih, V. K. Quality Control. *Bakery Products Science and Technology: Second Edition* **9781119967156**, 489–509 (2014).

21. Thanhaeuser, S. M., Wieser, H. & Koehler, P. Correlation of Quality Parameters with the Baking Performance of Wheat Flours. *Cereal Chem* **91**, 333–341 (2014).

22. Wang, K. Q. *et al.* Changes in chemical interactions and protein conformation during heat-induced wheat gluten gel formation. *Food Chem* **214**, 393–399 (2017).

23. Ma, H. *et al.* Relationship between the baking quality of wheat (Triticum aestivum L.) and the protein composition and structure after shading. *Food Chem* **441**, (2024).

24. Pareyt, B., Finnie, S. M., Putseys, J. A. & Delcour, J. A. Lipids in bread making: Sources, interactions, and impact on bread quality. *J Cereal Sci* **54**, 266–279 (2011).

25. de Kock, S., Taylor, J., N Taylor S de Kock, J. R. & N Taylor, J. R. *Effect of Heat Treatment and Particle Size of Different Brans on Loaf Volume of Brown Bread*. *2028 (South Africa) Lebenesm.-Wiss. u.-Technol* vol. 32 http://www.idealibrary.com (1999).

26. Parenti, O., Guerrini, L., Mompin, S. B., Toldrà, M. & Zanoni, B. The determination of bread dough readiness during kneading of wheat flour: A review of the available methods. *J Food Eng* **309**, 110692 (2021).

27. Dessev, T. *et al.* Influence of Baking Conditions on Bread Characteristics and Acrylamide Concentration. *J Food Sci Nutr Res* **3**, 291–310.

28. Cereal Chem 1991 | Gas Retention of Different Cereal Flours. https://www.cerealsgrains.org/publications/cc/backissues/1991/Documents/CC1991a72.html.

29. Siswantoro, J., Prabuwono, A. S. & Abdulah, A. Volume Measurement of Food Product with Irregular Shape Using Computer Vision and Monte Carlo Method: A Framework. *Procedia Technology* **11**, 764–770 (2013).

30. Takata, K., Matsushita, K., Goshima, D., Nakamura, T. & Yamauchi, H. Analysis of the relationship between bread-making quality and dough stress during the proofing process using near-isogenic lines of 'Harunoakebono'. *Breed Sci* **69**, 478 (2019).

31. Gobbetti, M., Giuseppe, C. & Editors, R. *Basic Methods and Protocols on Sourdough Methods and Protocols in Food Science*. http://www.springer.com/series/16556.

32. Wang, T. Y. & Nguang, S. K. Low cost sensor for volume and surface area computation of axi-symmetric agricultural products. *J Food Eng* **79**, 870–877 (2007).

33. Castillo-Castaneda, E. & Turchiuli, C. Volume Estimation of Small Particles Using Three-Dimensional Reconstruction from Multiple Views. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* **5099 LNCS**, 218–225 (2008).

34. The Bread Loaf Volumeter | The Fresh Loaf. https://www.thefreshloaf.com/node/68659/bread-volumeter.

35. Volscan Profiler | Volume Measurement | Stable Micro Systems. https://www.stablemicrosystems.com/VolscanProfiler.html.

36. EBSCOhost | 162427708 | Creating a Digital 3D Model of the Dental Cast Using Structure-from-Motion Photogrammetry Technique. https://web.p.ebscohost.com/abstract?site=ehost&scope=site&jrnl=26268493&AN=162427708&h=Tl9sToD5wQfct7PJBXhM53RgT7fD5e%2fRgFrxyCKxGgkA1LW4fG2ENsk5H7ut%2f5yWzmAREM%2bfdYfnO2BdpsHz8w%3d%3d&crl=c&resultLocal=ErrCrlNoResults&resultNs=Ehost&crlhashurl=login.aspx%3fdirect%3dtrue%26profile%3dehost%26scope%3dsite%26authtype%3dcrawler%26jrnl%3d26268493%26AN%3d162427708.

37. Hassannejad, H. *et al.* A new approach to image-based estimation of food volume. *Algorithms* **10**, (2017).

38. Dehais, J., Anthimopoulos, M., Shevchik, S. & Mougiakakou, S. Two-view 3D Reconstruction for Food Volume Estimation. (2017).

39. Rahman, M. H. *et al.* Food volume estimation in a mobile phone based dietary assessment system. *8th International Conference on Signal Image Technology and Internet Based Systems, SITIS 2012r* 988–995 (2012) doi:10.1109/SITIS.2012.146.

40. Electronics, W. J. Human-Mimetic Estimation of Food Volume from a Single-View RGB Image Using an AI System HHS Public Access. **10**, (2021).

41. Yuan, Di. *et al.* An automatic electronic instrument for accurate measurements of food volume and density. *Public Health Nutr* **24**, 1248–1255 (2021).

42. Yuan, C. Di *et al.* Research on 3d reconstruction method and application of food in stroke patients based on rgb-d image. *J Mech Med Biol* **23**, 23 (2023).

43. Chen, H. C., Jia, W., Li, Z., Sun, Y. N. & Sun, M. 3D/2D Model-to-Image Registration for Quantitative Dietary Assessment. *Proc IEEE Annu Northeast Bioeng Conf* **2012**, 95–96 (2012).

44. Xu, C., He, Y., Khanna, N., Boushey, C. J. & Delp, E. J. MODEL-BASED FOOD VOLUME ESTIMATION USING 3D POSE. *Proc Int Conf Image Proc* **2013**, 2534 (2013).

45. Puri, M., Zhu, Z., Yu, Q., Divakaran, A. & Sawhney, H. Recognition and volume estimation of food intake using a mobile device. *2009 Workshop on Applications of Computer Vision, WACV 2009* (2009) doi:10.1109/WACV.2009.5403087.

46. Hassannejad, H. *et al.* A New Approach to Image-Based Estimation of Food Volume. *Algorithms* **10**, (2017).

47. Dehais, J., Anthimopoulos, M., Shevchik, S. & Mougiakakou, S. Two-view 3D Reconstruction for Food Volume Estimation. (2017).

48. Gao, A., Lo, F. P. W. & Lo, B. Food volume estimation for quantifying dietary intake with a wearable camera. *2018 IEEE 15th International Conference on Wearable and Implantable Body Sensor Networks, BSN 2018* **2018-January**, 110–113 (2018).

49. Electronics, W. J. Human-Mimetic Estimation of Food Volume from a Single-View RGB Image Using an AI System HHS Public Access. **10**, (2021).

50. Lo, F. P. W., Sun, Y., Qiu, J. & Lo, B. Food Volume Estimation Based on Deep Learning View Synthesis from a Single Depth Map. *Nutrients* **10**, (2018).

51. Lu, Y. *et al.* A multi-task learning approach for meal assessment. *Proceedings of the Joint Workshop on Multimedia for Cooking and Eating Activities and Multimedia Assisted Dietary Management* 46–52 (2018) doi:10.1145/3230519.3230593.

52. Agisoft Metashape: Agisoft Metashape. https://www.agisoft.com/.