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Terahertz imaging for non-invasive classification of healthy and cimiciato-infected hazelnuts

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ABSTRACT

The development of new non-invasive approaches able to recognize defective food is currently a lively field of research. In particular, a simple and non-destructive method able to recognize defective hazelnuts, such as cimiciato-infected ones, in real-time is still missing. This study has been designed to detect the presence of such damaged hazelnuts. To this aim, a measurement setup based on terahertz (THz) radiation has been developed. Images of a sample of 150 hazelnuts have been acquired in the low THz range by a compact and portable active imaging system equipped with a 0.14 THz source and identified as Healthy Hazelnuts (HH) or Cimiciato Hazelnut (CH) after visual inspection. All images have been analyzed to find the average transmission of the THz radiation within the sample area. The differences in the distribution of the two populations have been used to set up a classification scheme aimed at the discrimination between healthy and injured samples. The performance of the classification scheme has been assessed through the use of the confusion matrix on 50 samples. The False Positive Rate (FPR) and True Negative Rate (TNR) are 0% and 100%, respectively. On the other hand, the True Positive Rate (TPR) and False Negative Rate (FNR) are 75% and 25%, respectively. These results are relevant from the perspective of the development of a simple, automatic, real-time method for the discrimination of cimiciato-infected hazelnuts in the processing industry.

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1. Introduction

In recent years, hazelnut (*Corylus avellana*) cultivation is becoming more and more important in terms of areas invested and crop expected [1]. In addition to the countries where this species was traditionally cultivated, new countries such as Chile and Ukraine, have made big investments in the cultivation of this crop [1]. This development strategy is mainly driven by the confectionery industry, which requires greater and greater volumes of hazelnut production [2]. At the same time, the confectionery industry asks for raw hazelnuts free from defects and alterations in order to guarantee the consumers products with an acceptable organoleptic quality during the entire estimated shelf-life. There are several factors that can alter the quality of hazelnuts. Biological or chemical alterations may originate during the growth phase on the plant, during harvesting as well as during the long-term postharvest storage that this product undergoes [2]. Often, the altering phenomena generated in the orchard can amplify their detrimental effects during postharvest storage. One of the most detrimental alterations to hazelnut quality is caused by a group of insects belonging to the family of *Coreidae* (*Gonocerus acuteangulatus*) and *Pentatomidae* (*Nezara viridula, Palomena prasina*) [3]. In the last years, the problem has been exacerbated by the wide colonization of Europe and America areas by *Halyomorpha halys* (fam. *Pentatomidae*) also called brown marmorated stink bug [4]. *Halyomorpha halys* does not find natural antagonists in the newly colonized areas, therefore it is particularly harmful, not only for hazelnuts but also for many other crops (e.g. peaches, apples, or pears) [5].

On hazelnuts, stink bugs can cause different types of damage, depending on the stage of development in which the fruit is hit. In particular: i) if the insect bites the fruit in the pre-expansion phase of the shell, hazelnuts will be almost certainly subject to drop or traumatic abortion; ii) if the fruit is bitten while the shell is expanding, a traumatic abortion of the kernel will almost always occur, therefore shells will be empty at harvest; iii) if the fruit is hit during the kernel expansion or the ripening phase, kernels will be shrivelled or they will present a high incidence of the characteristic off-flavour defined as “cimiciato” or “corked” [3–6]. By visual inspection, cimiciato defect can appear as one or more spots on the kernel surface (external or visible cimiciato) or the damage can be located inside the kernel, and this prevents it to be detected visually, but the injure becomes visible only after opening the fruit in two halves (hidden or internal cimiciato) [6].

Cimiciato defect is particularly detrimental because the affected hazelnuts become bitter and astringent, due to the presence of a pool of diarylheptanoids (such as asadanin, giffonin P, and other congeners) [7,8]; moreover a typical and unpleasant aroma occurs, due to volatile compounds deriving from lipid oxidation as well as to other potent odorants potentially responsible for the aroma off-notes [9–11]. The incidence of cimiciato defect is strongly related to year, cultivar and growing area. For example, in southern Italy in some cultivars the incidence of damage can even reach 35% [6], while in Turkey, on the basis of the cultivation area and season, the incidence of damage varies between 1.5% and 20% [12].

Due to the detrimental effect of cimiciato defects on hazelnut quality and shelf-life, the international standards set several tolerance limits. The United Nations Economic Commission for Europe (UNECE) sets a tolerance limit of one spot on the kernel that does not exceed 3 mm in diameter by 3 mm in depth [13], while according to the Organization for Economic Co-operation and Development (OECD) the kernel must not be affected and the spot on the skin must not exceed 3 mm in diameter [14].

Nowadays, the hazelnut selection in industry is usually made by manual sorting based on visual inspection, a method extremely time- and labor-consuming, often lacking in standardization and accuracy, also because of the small size of the product.

In this context, non-invasive methods for the automatic determination of injured hazelnuts are strongly requested by the industry, in order to reduce the production costs and to standardize the production process.

Near infrared (NIR) spectroscopy was the most studied non-destructive technique for the hazelnut quality control in terms of moisture and acidity [15], flawed kernel (surface mold and dark skin color) and lipid oxidation [16]. Nuclear magnetic resonance (NMR) has been shown to be useful for the detection of undeveloped hazelnuts, moldy hazelnuts, and kernel moisture in in-shell hazelnuts [17]. As for cimiciato-infected hazelnuts detection, Red-Green-Blue (RGB) image analysis was found to be reliable to identify cimiciato damage on halved hazelnuts [18], however hazelnuts used for direct consumption and most of those destined to industry need to be selected whole. Moreover, being a surface analysis, RGB method would not be able to detect hidden cimiciato defect, therefore this method is not able to guarantee a complete selection of the product. From this point of view, the use of a Terahertz imaging for the identification of defective hazelnuts could improve the selection process even for hidden cimiciato fruit. Moreover, terahertz setup can be easily integrated into an industrial sorting process and no studies have been conducted to date on the application of terahertz imaging for hazelnut quality control.

Terahertz (THz) radiation commonly refers to the frequency band of the electromagnetic spectrum between 0.1 THz and 10 THz. THz waves penetrate organic materials such as dry skin, plastics, cloth, dry food, or paper, while they are reflected by metallic materials. Carrying low energy photons, THz radiation is unable to induce ionization processes, differently for instance from X-rays, which means that it is a perfectly safe radiation for biological tissues. This explains the interest in THz based methods for many different applications [19] like in the biomedical field [20–25], chemistry [26], biological detection [27], plant monitoring [28–31] and security controls [32].

Moreover, vibrational and rotational response of molecules, e.g. water, in the THz range provides information which cannot be obtained with analogous techniques [19,33]. THz spectroscopy and imaging are versatile techniques that can provide information both on the chemical and on the structural characteristics of a sample. For example, volatile chemical components have been detected in gas phase by a high-resolution THz setup [34], different tissues have been recognized through the use of a quantum cascade laser source [35], and the internal structure of an object has been retraced by THz tomography [36]. Continuous-wave THz transmission imaging has been demonstrated to be a suitable tool for different purposes [21], offering at the same time the basic advantage of practically instantaneous measurement times as well transmissive properties which allows its application in non-invasive detection techniques for the food industry. In fact, this technique has already been proposed for quality assessment of food products, such as in peanuts [37] and

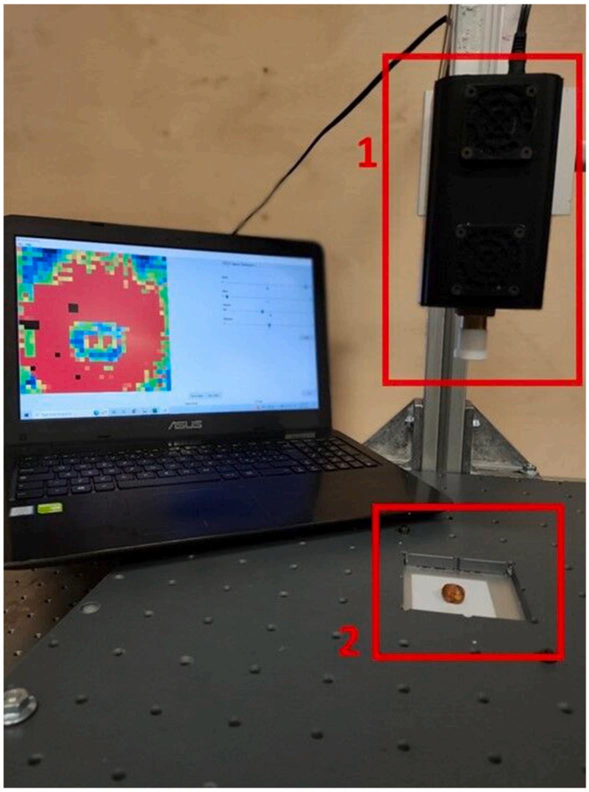

Fig. 1. Terahertz measurement setup for hazelnut imaging. 1: Terahertz source, 2: Terahertz camera.

in chocolates [38] or for example to detect the plumpness of sunflower seeds [39], to detect the presence of foreign bodies in grain [40] and sausages [41] or to assess the presence of fungi in chestnuts [42]. Recently, an attempt to discriminate between healthy and rotten hazelnuts with imaging in the GHz range has been presented [43], but images are obtained by raster scanning the sample leading to complicated setup and long acquisition times, that make this approach unsuitable for practical applications. Moreover, the work has been carried out on a very small sample (5 healthy and 5 rotten hazelnuts) and no quantitative results are presented in terms of classification of the hazelnuts.

The aim of this work was to develop and validate a continuous-wave THz transmission imaging system to discriminate the presence of stink bug injuries on whole hazelnuts. Being a fast and non-invasive method, it could be potentially implemented in real time sorting on industrial production lines.

2. Materials and methods

2.1. Hazelnuts samples

The trial was conducted on hazelnut kernels (*Corylus avellana* L.) cultivar Tonda di Giffoni, harvested in September 2021 in a private orchard in Presenzano (CE) Italy, managed under organic farming practices. After harvesting, the hazelnuts in shell were transported to the industrial processing center V. Besana SpA (San Gennaro Vesuviano, NA, Italy) where they were washed, dehydrated at 6% (in accordance with UNECE directives, 2010) and separated by size classes.

Subsequently, the hazelnuts were packed under vacuum in plastic bags and stored in the dark, at constant temperature and relative air humidity (60%), in accordance with the industrial storage protocol.

In June 2022, 10 aliquots of 0.5 kg each were randomly taken from a sample of approximately one ton of hazelnuts in shell of the most representative size class (17–21 mm). From the mix of these aliquots, a calibration sample and a validation sample were randomly taken. The calibration sample consisted of 150 hazelnuts and it was used for setting up the classification model. Immediately before the THz analysis, this sample was shelled manually and visually inspected. A sub-sample of 110 kernels free from any defect (Healthy Hazelnuts, HH) and one of 40 kernels injured by stink bugs (Cimiciato Hazelnuts, CH) were identified. The validation sample consisted of 50 hazelnuts and it was used to blindly evaluate the performance of the classification model. Each hazelnut was manually shelled and a THz picture was taken for the classification. Eventually, visual inspection confirmed or rejected this classification.

Fig. 2. Example of a healthy (A, HH) and a cimiciato hazelnut (B, CH).

2.2. Terahertz setup

All measurements were conducted at the University of Pisa, Department of Physics "E. Fermi", Pisa, Italy (43°43′14''N 10° 24′ 23''E). The terahertz (THz) imaging system (Fig. 1) was composed of an impact avalanche transit time diode source [44] (IMPATT-100-H/F, Terasense, San Jose, USA, inset 1 in Fig. 1) with a nominal output power of 30 mW and an output frequency of 140 GHz, and a THz camera (T15/32/32, Terasense, San Jose, USA, inset 2 in Fig. 1) composed by a square matrix of sensors (32 × 32 pixels). We used a 0.140 THz continuous wave source because relatively low-cost sources and detectors can be bought in this region and because this setup is compact, easy to operate and permits fast detection. Moreover, no detailed investigation on hazelnut fruits using this technology has already been proposed in the literature. The distance between the diode source and the THz camera was 40 cm. This distance was optimized to have the most uniform illumination possible in the area occupied by the hazelnut on the detector. Moreover, the exposure time of the image was optimized in order to avoid saturation of the pixel signal. The gamma correction was kept fixed to the value corresponding to linear response of the pixels in order to ensure a better reproducibility of the results between repeated acquisitions.

2.3. Data analysis

2.3.1. Image analysis

The analysis of THz images, and the following statistical elaborations, were performed using Matlab software (version R2021a). As a first step, the area occupied by the nut was determined using the MATLAB function "find circles", a tool capable of recognizing a circular object from the background. Then, each image was cropped to cut the noise coming from the area outside the nut. Furthermore, the average intensity of the signal in the cropped area was calculated both for the nut image and for the background image acquired without any fruit on the sensor. The mean attenuation in the fruit area was then calculated as the ratio between the two average intensities. In formula:

$$A = \frac{\sum_{i,j} I_{bkg_{i,j}}}{\sum_{i,j} I_{nut\,i,j}} \quad [1]$$

where I_{bkg} was the background intensity, I_{nut} was the sample intensity, and the i and j indexes run over all the pixels in the cropped area.

2.3.2. Classification model

As a further analysis, a method for assigning hazelnuts of unknown nature to one of the two populations was implemented. The MATLAB "probability plot" function was exploited to plot the two distributions (HH and CH). This function plots the data with a nonlinear y-axis. The distance between tick marks on the y-axis is either compressed or stretched to match the distance between the quartiles of a normal distribution so that sample data belonging to a normal distribution will appear along a straight line.

The plot of the two distributions was exploited to create calibration curves to be used as a reference for testing the unknown hazelnut samples, i.e., the validation sample. The calibration curves were created using the parameters of the curves that best fit the distribution.

Once the two calibration curves had been created, we added a new data point to each of the two distributions, and we calculated the minimum distance between this new point and the fitting function using the MATLAB "Symbolic Math Toolbox". The new data point was, then, assigned to the distribution with the lower distance.

Finally, the confusion matrix was used to summarize the results and evaluate the performance of the methodology. This matrix reports the number of True Positive (TP), True Negative (TN), False Positive (FP) and False Negative (FN) results. The first two elements represent the successful cases, i.e., the number of HH samples predicted to be HH and the number of CH samples predicted to be CH. The last two elements represent the cases where the methodology fails, i.e., the number of CH elements predicted to be HH and the

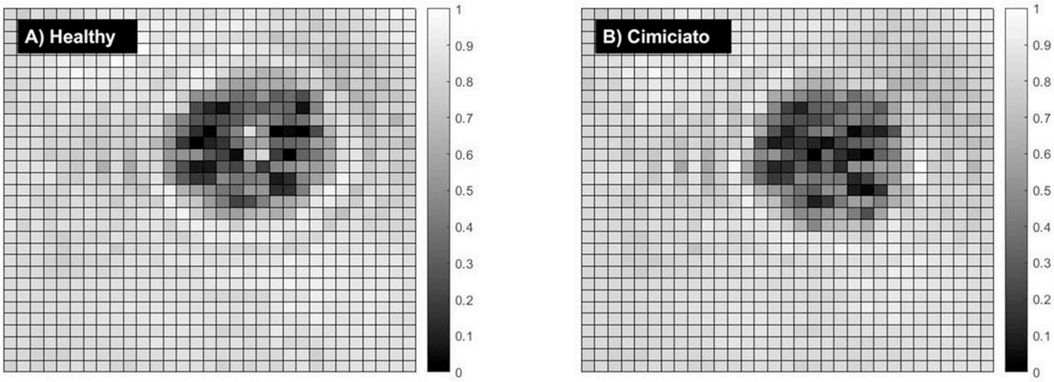

Fig. 3. (A) Example of a healthy hazelnut (HH) THz image. (B) Example of a cimiciato hazelnut (CH) THz image. In both images, the hazelnut area is darker than the surrounding, indicating an attenuation of the THz signal. The percentage of radiation attenuation is shown as a colorbar. 1 means 100% absorption, 0 means 0% absorption.

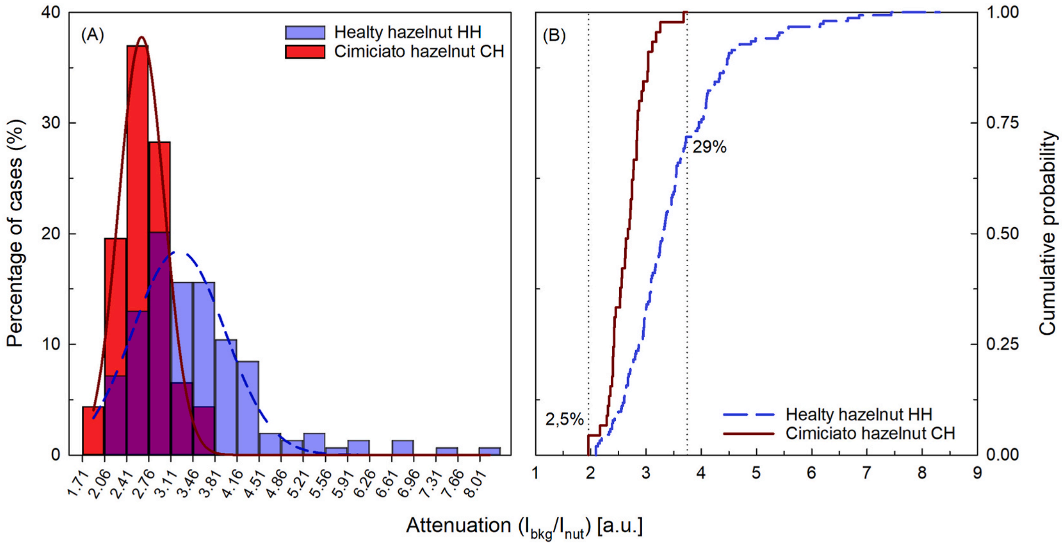

Fig. 4. Results of Terahertz imaging analysis of healthy hazelnuts (HH) and cimiciato hazelnuts (CH) represented as A) distribution of the attenuation values with the respective probability curves superposed (B) Cumulative probability of the attenuation values.

number of HH elements predicted to be CH.

In order to evaluate the performance of the created method, a series of figures of merit were calculated using the results included in the confusion matrix, such as:

True Positive Rate (TPR): 100*TP/(TP+FN): it represents the sensitivity of the methodology, that is the probability of having a predicted HH analyzing a HH.

True Negative Rate (TNR): 100*TN/(TN+FP): it represents the specificity of the methodology, that is the probability of having a predicted CH analyzing a CH.

False Negative Rate (FNR): 100*FN/(FN+TP): it represents the Type 1 error. It quantifies the number of mistaken rejections of HH.

False Positive Rate (FPR): 100*FP/(FP+TN): it represents the Type 2 error, that is the number of missing rejections of CH.

3. Results and discussion

3.1. Analysis of the physical parameters

As a first step, a picture of each kernel was taken with a standard cell-phone camera (smartphone model: Find X2 Neo, OPPO, Dongguan, China) to create a database as complete as possible. Fig. 2a and b shows examples of a healthy (HH) and a cimiciato hazelnut (CH). Although some differences can be found between these two images, we were not able to find an automatic procedure to distinguish between HH and CH sub-samples due to the variability of the biological samples. In fact, the majority of the samples did not

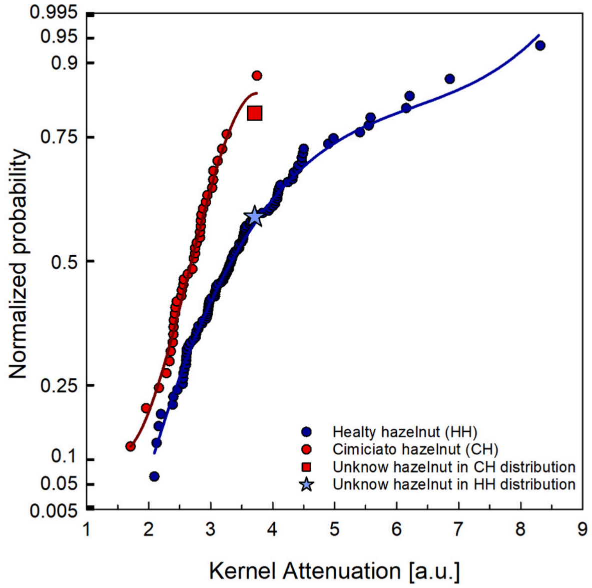

Fig. 5. Probability plot of the two different distributions of healthy hazelnuts (HH) and cimiciato hazelnuts (CH) with the fit superimposed and an example of placing an unknown hazelnut in the HH (star) and CH (square) distributions. On the basis of the distance from the fitting function, this hazelnut was assigned to HH.

present such a visible cimiciato mark, or it could be covered by the hazelnut skin. On the other hand, the hazelnut skin could show marks that were not caused by stink bugs.

3.2. Analysis of the THz pictures

Fig. 3a and b shows examples of THz pictures of a HH and a CH after subtraction of the background image. Despite the low resolution of the images, some observations can be made on the intensity distribution within the nut area. The intensity value read by each pixel depends on the intensity of the radiation impinging on it. As expected, the intensity within the nut area is lower than the intensity outside the nut and this clearly indicates that part of the radiation is absorbed inside the sample. Usually the intensity tends to decrease almost symmetrically starting from the nut boundaries towards the center, but sometimes a peculiar effect could be observed. The central area of the nut presents an increase of the signal exactly as if the radiation were not absorbed. Sometimes, this intensity is even comparable to the background intensity, as in the image of the healthy nut in Fig. 3. This effect cannot be interpreted as a lower absorption from the central part of the nut, because this is also the thickest region travelled by the radiation. Instead, we interpreted it as a kind of 'lens effect' produced by the spherical shape of the nut. This effect modifies the spatial distribution of the intensity of the various pixels of the image, but, assuming a linear response of each pixel, the average signal over the nut area can still be assumed to be a good indication of the overall attenuation introduced by the presence of the sample. For this reason, we took particular care in avoiding saturation of the signal by optimizing both the source-detector distance and the exposure time, as reported above.

For each THz image data, we computed the average attenuation with the equation [1] and performed a statistical analysis on these results. Results are reported in Fig. 4. Fig. 4A shows the histograms of the distribution of the attenuation values and Fig. 4B shows the same results as cumulative probability plot. As one can see, the CH sample tends to have lower attenuation levels, although there is not a complete separation between the two histograms. This means that the radiation was less attenuated by the CH sample if compared to the HH one, but a simple discrimination of the tails of the two distributions would allow to select only 2.5% of the injured hazelnuts and 29% of the healthy ones, leaving a large portion of both distributions superimposed, as highlighted by the cumulative probability distribution. The lower absorption observed for the damaged hazelnuts (CH) could be likely due to the presence of structural alterations in the tissue stung by the stink bug. Indeed, among the effects of stink bug injuries, the occurrence of dry, necrotic tissue in cimiciato-infected hazelnuts is reported [45]. Moreover, the watery saliva of the stink bugs transfers into the nuts several hydrolyzing enzymes, such as protease, amylase, esterase, and lipase [46], therefore also enzymatic reactions involving hazelnuts components may play a role in modifying THz absorption.

3.3. Classification model

We plotted the probability plot of the two distributions of HH and CH samples and fitted them with a third-degree polynomial function, as explained in Section 2.3.2. Fig. 5 shows the probability plot of the two different distributions with the fit superimposed. In the same figure, we show an example of a hazelnut taken from the validation sample added to both the HH and CH distributions for its assignment (Fig. 5). The value of the calculated transmission of a single hazelnut corresponds to a different probability value when

Table 1
Confusion matrix and performance indices of the prevision model developed. Healthy hazelnuts (HH), cimiciato hazelnuts (CH) True Positive (TP), True Negative (TN), False Positive (FP), False Negative (FN), True Positive Rate (TPR), False Negative Rate (FNR), False Positive Rate (FPR) and True Negative Rate (TNR).

Total Population: 44 + 6 = 50		Predicted condition			
		HH: 33	CH: 17		
Actual condition	**HH: 44**	TP:33	FN:11	**TPR: 33/44 = 75%**	**FNR: 11/44 = 25%**
	CH: 6	FP: 0	TN:6	**FPR: 0/6 = 0%**	**TNR: 6/6 = 100%**

added to the two different distributions, therefore it appears in two different y positions in the plot. Moreover, the addition of a data point slightly modifies the probability plot itself, but the fit used for the calculation of the distance (and reported in the figure) still refers to each distribution without the new data point. The same point was plotted with two different marks, the square represents the point added to the cimiciato distribution, whereas the star represents the point added to the healthy distribution. In this case, the sample was assigned as HH because, as we can see from the figure, the distance between the star symbol and the line of the HH fit is lower than that between the square symbol and the line of the CH fit. The procedure was repeated for all the hazelnuts of the validation sample.

Finally, the correct assignment to HH or CH class was verified manually by visual inspection. These results are reported in the electronic supplementary information (Table 1s).

As we can see from Table 1s, we were able to successfully identify 6 out of 6 CH and 33 out of 44 HH tested.

Table 1 shows the confusion matrix built with the results presented above. TPR and TNR are the two figures of merit that characterize the accuracy of our methodology and represent the sensitivity and the specificity of the system.

As we can see from Table 1, the False Positive Rate (FPR) and True Negative Rate (TNR) are 0% and 100%, respectively. On the other hand, the True Positive Rate (TPR) and False Negative Rate (FNR) are 75% and 25%, respectively. The accuracy of the method was calculated as $A = 100*(TP+TN)/(TP+FN+FP+TN) = 39/50 = 78\%$. The classification method was able to correctly identify 100% of cimiciato hazelnuts in the unknown sample, thus showing a perfect specificity (TNR), with a somewhat lower sensitivity (TPR).

These results offer a fast and easy method to predict if a whole nut is healthy or cimiciato-infected. Other recent approaches have obtained similar results on pine nuts or walnuts [47–49], for example, but in all these cases, the system consists of a point-wise acquisition of raster-scanned images followed by a complicated image processing analysis that also involves the use of artificial intelligence techniques. This means that the setup is expensive and bulky, the acquisition is slow and data processing requires large computational resources. Our approach relies on a much simpler and cheaper apparatus that can be easily used in the field, and in a fast and simple data analysis that can be easily implemented on any personal computer in real time.

4. Conclusions

A classification method for the detection of cimiciato-infected hazelnuts through the use of a simple THz imaging system was presented. This technology has already been used for other food samples [42,50]. In this work, the images obtained in the THz range from the analysis of a sample constituted by healthy and cimiciato-infected hazelnuts were used to build two calibration distributions, which were employed to develop the classification model. The developed classification model was then applied to the analysis of a validation hazelnut sample and the correct assignment was verified by visual inspection (the usual method nowadays employed by the industry). The model showed an excellent prediction ability, with a True Negative Rate of 100% and a False Positive Rate of 0%. This means that all the cimiciato-infected hazelnuts in the sample were correctly identified. On the other hand, the True Positive Rate (TPR) and False Negative Rate (FNR) were 75% and 25%, respectively, thus showing a somewhat lower sensitivity. These results suggest that a continuous-wave terahertz transmission imaging system can be a viable approach for the recognition of defective hazelnuts before their commercialization or processing. This method is experimentally simple, automatable, it requires a low-cost apparatus and can potentially be implemented in real-time, therefore, it can be of great interest for the food industry.

Work is in progress to improve the resolution and signal-to-noise ratio of the images through the use of a high-resolution camera that works at higher frequency. Moreover, artificial intelligence techniques will be used for the real-time analysis of the images. This is expected to greatly improve TPR and FNR.

Author contribution statement

Fulvia Gennari, Mario Pagano: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Alessandra Toncelli: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Maria Tiziana Lisanti: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Riccardo Paoletti: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Pio Federico Roversi: Conceived and designed the experiments.

Alessandro Tredicucci, Matteo Giaccone: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e19891.

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