Vol. 15, No. 4 (2026): 1439 - 1447 http://dx.doi.org/10.23960/jtepl.v15i4.1439-1447

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Non-Destructive Method for Evaluating Viability of Watermelon and Tomato Seeds Using Radiographic Imaging

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Article History:

Received : 02 March 2026
Revised : 03 August 2026
Accepted : 11 August 2026

Keywords:

Germination test,
Radiographic,
Seed viability,
Tomato,
Watermelon.

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ABSTRACT

Conventional germination testing is the reference method for determining seed viability, but it is time-consuming and requires test samples. This study was conducted to evaluate the feasibility of industrial radiographic imaging as a non-destructive technique for identifying the internal structural condition of watermelon and tomato seeds and predicting their viability. A total of 608 seedless watermelon seeds and 700 tomato seeds were individually tagged, radiographically imaged, visually graded for embryo and endosperm integrity, and then subjected to standard germination tests for validation. Watermelon seeds were categorized into five radiographic grades based on the completeness of the embryo/endosperm, and tomato seeds were classified according to the presence of a complete internal cochlear-like structure. Sensitivity, specificity and accuracy were calculated for the radiographic classification and evaluated with a seed-by-seed confusion matrix. Radiographic imaging showed promising performance in detecting germinable seeds in both watermelon and tomato, with high sensitivity and an overall accuracy of about 92%. These results show that radiographic imaging is a promising non-destructive screening method, in particular for larger seeds with clearly visible internal structures. However, it must be seen as a rapid screening method for complementary purposes and not as a complete substitute for the standard germination test. Additional work should include quantification of image analysis, testing for agreement between evaluators, and automatic classification to increase robustness.

1. INTRODUCTION

Seed viability is a fundamental indicator of seed physiological quality because it refers to a seed's capacity to remain alive and sustain growth (Ghodasaini & Ghimire, 2022). Seed viability and seed vigor are closely related but represent different aspects of seed quality; viability reflects the ability of a seed to germinate, whereas vigor describes its potential for rapid and uniform emergence under a wide range of environmental conditions (Jin *et al*., 2022). In seed quality control, a seed viability test is any method used to assess whether individual seeds in a sample are alive or dead, allowing the percentage of living seeds in a population to be estimated (Pradhan *et al*., 2022). In Indonesia, the most commonly used conventional germination testing for assessing viability is conducted by the International Seed Testing Association (ISTA). These include seed germination, tetrazolium test, and electrical conductivity, which provide results within a few days (França-neto & Krzyzanowski, 2019; Men *et al*., 2017). However, these methods require several days to weeks, depending on the crop species and consume the tested samples, making it less suitable for rapid screening of valuable seeds, breeding materials, or seed lots requiring repeated monitoring.

Rapid and non-destructive evaluation methods are increasingly required for effective seed testing because they enable repeated assessment of valuable seed lots while preserving their ability to germinate (Jin *et al*., 2022). Although the tetrazolium test is rapid, it can potentially damage seed samples, making them unusable (Rodrigues *et al*., 2018). Therefore, alternative, non-destructive methods for assessing seed viability have been developed, such as digital imaging. This technology can be used to automatically and quickly evaluate seed viability without damaging the sample, making it a more objective and effective method. However, most digital imaging methods developed for seed viability testing rely on expensive, sophisticated, and technically complex systems, while research on affordable and accessible alternatives is still limited (Mahajan *et al*., 2018; Singh *et al*., 2025). However, detecting seed condition solely from its external appearance is difficult. Therefore a digital imaging system capable of penetrating the seed coat to reveal its internal structure is essential, especially the healthy seeds typically have large embryos with few cavities (Zhang *et al*., 2023).

Non-destructive methods for testing seed viability include a variety of advanced technologies, such as near-infrared spectroscopy, hyperspectral and multispectral imaging, Raman spectroscopy, infrared radiation thermography, and Radiographic imaging (N'dri-Aya & Vroh-Bi, 2024; Singh *et al*., 2025; Xia *et al*., 2019). Radiographic imaging, such as X-ray, serves as a robust non-destructive technique that penetrates the seed coat to directly visualize internal morphological traits, enabling the quantification of structural integrity, internal cavity dimensions, and embryonic development without damaging the sample (Hong *et al*., 2023). Near-infrared spectroscopy involves the absorption of electromagnetic radiation within a specific wavelength range (Nicolaï *et al*., 2007). The key benefit of a non-invasive test is safeguarding seeds, enabling ongoing monitoring, and minimizing the waste of valuable seeds. This is particularly beneficial for seed companies and conservation institutions, where maintaining a viable seed supply is crucial (Bianchini *et al*., 2021). For instance, Fourier Transform near-infrared spectroscopy (FT-NIR) combined with partial least squares-discriminant analysis (PLS-DA) has shown promising results in accurately classifying corn seed viability at 100% accuracy (Ambrose *et al*., 2016), pepper seeds at 90.5% accuracy (Seo *et al*., 2016), and for various seeds with accuracy around 70,85% (Singh *et al*., 2025). However, the performance of NIR and other spectral imaging methods strongly depends on calibration models, spectral preprocessing, seed type, and chemical differences between viable and non-viable seeds, which may limit their broader application, especially in industry. Spectroscopy provides detailed molecular information but is often affected by fluorescence interference, requires highly sophisticated instruments and technologies and complex processing. Additionally, although spectral imaging methods can capture chemical denaturation—such as protein changes around the 900–908 nm wavelength range—radiographic imaging offers the distinct advantage of directly visualizing physical structural defects (Hong *et al*., 2023). Similarly, IRT is useful for detecting thermal responses associated with seed moisture and metabolic activity, but it provides only indirect information on internal seed structure. On the other hand, radiographic imaging enables direct visualization of internal morphological features, such as embryonic development, endosperm integrity, mechanical damage, and internal cavities, without destroying the seed. Another notable technique is hyperspectral and multispectral imaging, which integrates spectroscopic and imaging methods to generate detailed monochromatic images with numerous wavelength variations for analyzing the spatial distribution of components. Raman spectroscopy (RS) is a spectroscopic analysis technique based on Raman scattering and vibrational frequencies specific to chemical bonds and molecular symmetry. Huang *et al*. (2025) was applied RS in detecting the quality of fruit such as diseases, pesticide residues, and origins.

Moreover, Infrared radiation thermography (IRT) technology offers a cost-effective alternative with superior imaging capabilities compared to hyperspectral imaging and FT-NIR. IRT can produce two-dimensional thermal images for target plane comparisons (Usamentiaga *et al*., 2014). Lastly, Radiographic imaging employs electromagnetic radiation within a specific wavelength range to provide insights into internal morphological characteristics for assessing seed viability, as demonstrated in a recent study on muskmelon seeds.

According to Ma *et al*. (2020), hyperspectral near-infrared (NIR-HSI) and convolutional neural networks (CNNs) are employed with deep learning for seed viability testing. The selection of this camera is based on its capability to detect both molecular vibrations and the spatial distribution within each seed sample. The use of this camera is deemed more informative than that of standard RGB digital cameras. Additionally, CNNs are used to differentiate between living and dead seeds for subsequent classification. A classification accuracy of 90% was achieved in validating these techniques against natural hatcheries.

Moreover, Pang *et al*. (2021) suggest that integrating deep neural networks and hyperspectral imaging into *Sophora japonica* viability studies could enhance seed viability testing by combining deep learning methods with high-precision spectral or image identification. This study also recommends the application of a particle swarm optimization (PSO) algorithms to increase object recognition and improve convergence speed. Research on predicting pepper seed germination using a combination of hyperspectral and Radiographic (digital imaging) techniques achieved the highest accuracy of 92.51% (Hong *et al*., 2023). Furthermore, deep learning approaches offer the advantage of synchronous model updating, allowing classification accuracy to continually improve as more training data are incorporated (Ma *et al*., 2020).

Based on previous research, it was hypothesized that optimal accuracy in seed viability testing could be achieved by combining hyperspectral and Radiographic imaging with deep learning methods. After all, digital imaging systems can be expensive to acquire, necessitating the exploration of more cost-effective alternatives. As highlighted in a presentation by Drs. Ruojing Wang and Bert van Duijn at the International Seed Quality Assurance (ISTA) Congress in Cairo, Egypt, on August 5, 2022, they identified financial constraints as major barrier to the adoption of new seed testing technologies. This challenge underscores the need for cost-effective non-destructive seed testing systems. Therefore, this research aims to develop an effective non-destructive testing approach based on radiographic imaging to evaluate the viability of watermelon and tomato seeds.

2. MATERIALS AND METHODS

2.1. Seed Materials

This study used 608 seedless watermelon seeds (Amara F1) and 700 tomato seeds (Servo F1) obtained from PT East West Seed Indonesia. Watermelon and tomato seeds were selected to represent seeds with contrasting physical dimensions and visibility of internal structure. Watermelon seeds represented larger seeds, whereas tomato seeds represented smaller seeds. Prior to imaging, each seed was assigned an individual identification code to ensure that radiographic classification could be matched with the corresponding germination result.

2.2. X-ray, Scanner, and Image Plate Specification

In this study, seed radiographic images were acquired using an X-ray generator and an HD-CR 35 NDT scanner (DÜRR NDT, Germany) equipped with a UH Blue imaging plate. The scanning procedure was performed using an actual tube voltage of 10-70kV, tube current of 10-30mAs, and exposure time of 10-30 s. During image acquisition, the seeds were positioned 50-80 cm from the X-ray source to obtain clear internal structures. The resulting radiographic images were digitized at 16-bit grayscale. These parameters were selected to provide sufficient contrast to observe internal seed features, including embryo development, endosperm integrity, and internal cavities, which are relevant to seed viability evaluation.

Viability testing assesses the germination potential of seeds by sowing them under ideal conditions. Nevertheless, the seeds tested cannot be reused for planting due to impairment. For this study, non-invasive testing was performed using Radiographic imaging. A total of 700 tomato seeds and 608 seedless watermelon seeds were used. The viability of the samples used is unknown, and they were selected randomly. The dataset was divided into training and testing sets using a 70:30 split, with randomization performed before data partitioning to minimize sampling bias. No experimental replication was applied because the analysis was conducted at the level of individual seeds, with each seed treated as an independent observation. The seeds were placed on acrylic plates for easy identification, ensuring their preservation during the evaluation process.

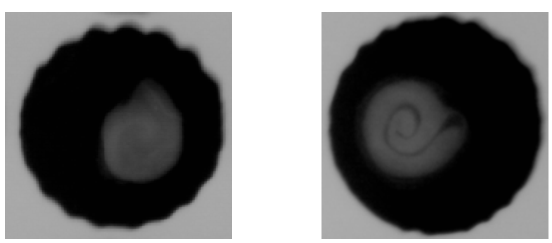
Initially, the seeds were placed on a blue plate for exposure to an Radiographic machine from a designated manufacturer, after which the plates were scanned with a specific brand of scanner. The seeds are then categorized into various grades based on embryo and endosperm characteristic (Table 1, Figure 1, and Figure 2). It is understood that viable seeds exhibit optimal germination potential when the conditions of the embryo and endosperm are healthy. An embryo is a young sporophyte that possesses the structural components and essential information required to initiate a new life during germination, while the endosperm serves as an abundant source of nutrients, including phytohormones, which are crucial for embryo development and subsequent germination (Yeung, 2022).

Table 1. Watermelon and tomato seed grading classification

Watermelon Seed			Tomato Seed	
Grade	**Embryo and endosperm condition**	**Criteria**	**Grade**	**Condition**
A	Whole and full	Viable	Viable (V)	There is a full conch-house-like shape
B	¾ Part	Viable	Non Viable (NV)	No cochlear shape/not full
C	2/3 part	Viable		
D	Have faults or cracks	Viable		
E	Do not have embryo and endosperm	Non viable		

(a) (b) (c) (d) (e)

Figure 1. (a) Whole and full embryo and endosperm of watermelon seed condition, (b) ¾ embryo and endosperm of watermelon seed condition, (c) ⅔ embryo and endosperm of watermelon seed condition, (d) have faults or cracks embryo and endosperm of watermelon seed condition, (e) do not have embryo and endosperm



(a) (b)

Figure 2. Tomato seed: (a) With a full conch-house-like shape, (b) No cochlear shape/not full tomato seed

2.3. Germination Method

In the second phase of the study, all seeds underwent germination testing to confirm the accuracy of the evaluation outcomes obtained through Radiographic scanning. Using the A1000 Growth Chamber by Conviron in Canada, the germination process for watermelon seeds involved rolled paper testing. Initially, the watermelon seeds were subjected to imbibition through sacrifice. Subsequently, the seeds were placed on three damp sheets of paper, covered with two additional sheets, rolled, and then positioned in a plastic container stored in the growth chamber. Seed germination observations were conducted on days 5 and 8, with the growth chamber set at 30 °C and full-day lighting. In contrast, tomato seed germination required a different approach, with the settings adjusted to 12 hours at 20 °C and 12 hours at

30 °C. The tomato seeds were arranged on two sheets of paper, with a layer of tissue paper between them, and covered with an additional sheet of paper. Observations were made on the 5th and 14th days.

The germinated seeds are evaluated by counting the germination rate and then classified into three categories: normal, abnormal, and dead. Normal seeds should have normal seedlings measuring>1 cm, free from spots or signs of disease. Abnormal seeds have weak, short ridges or defective germination (Upadhyaya *et al*. 2008), while dead seeds are those that fail to germinate (not dormant) and exhibit rotten seeds. The final classification results are viable and non-viable, and are then compared with the Radiographic grading results for the seeds. To determine the accuracy of the Radiographic method relative to the conventional germination test, the sensitivity (true-positive rate) and accuracy must be calculated. Accuracy calculated by using Equestion 1 and 2:

$$Sensitivity = \frac{TP}{TP+FN} \tag{1}$$

$$Accuracy = \frac{TP+TN}{Total} \tag{2}$$

where TP (True Positives) is seeds identified as viable by both the Radiographic and germination test; TN (True Negatives) is seeds identified as non-viable by both (Radiographic and germination test); FP (False Positives) is seeds identified as viable by Radiographic but non-viable by germination test; and FN (False Negatives) is seeds identified as non-viable by Radiographic but viable by germination test

3. RESULTS AND DISCUSSION

In this study, watermelon (*Citrullus lanatus*) and tomato (*Solanum lycopersicum* L.) seeds were assessed using a combination of non-destructive industrial Radiographic imaging and manual germination tests. Radiographic images effectively highlight structural defects such as internal void spaces, tissue cracking, and incomplete embryo expansion, which are major physical indicators associated with low germination potential (Hong *et al*., 2023). The same seed samples were subjected to industrial Radiographic scanning to observe internal structural integrity, followed by individual labeling to ensure accurate sample identification throughout the experiment. After Radiographic exposure, the labeled seeds were germinated manually under controlled conditions. During the interval between Radiographic imaging and germination, storage conditions, such as temperature and humidity, were carefully controlled to minimize external factors that could affect seed viability. This approach allows for a direct relationship between the internal structure of seeds observed via Radiographic imaging and seed viability as measured by germination.

Figure 3 compares radiographic images with conventional germination test results for seedless watermelon and tomato seeds. The radiographic image of seedless watermelon seeds (Figure 3a) shows a relatively clear contrast between the seed coat and the internal seed structure, allowing visual assessment of embryo development and internal filling. Seeds with well-developed internal structures, higher internal density (shown as white color), and fewer empty spaces were more likely to produce normal seedlings in the germination test (Figure 3b). This pattern aligns with observations in other solanaceae seeds, where non-viable seeds tend to be associated with significantly wider internal cavity spaces and underdeveloped embryos (Hong *et al*., 2023). In contrast, seeds with poorly developed internal structures, larger internal cavities, or irregular density distribution may be associated with non-viable seeds or abnormal seedling development. These visual characteristics indicate that radiographic imaging is useful for identifying structural defects that are not visible from the external seed appearance.

For tomato seeds, the radiographic image (Figure 3c) shows a smaller seed size and more compact internal structures compared with those of seedless watermelon seeds. This condition may reduce the visibility of the embryo and endosperm boundaries, making visual classification more difficult. The tomato endosperm is spiral-shaped, unlike the watermelon endosperm, which is oblong or heart-shaped. The smaller size of tomato seeds may also increase the possibility of misclassification because minor differences in internal density are less clearly observed. When the same imaging resolution is used, smaller seeds may occupy fewer image pixels, so the embryo, endosperm, and small internal cavities become more difficult to distinguish. This finding is consistent with the lower classification performance observed in tomato seeds compared with seedless watermelon seeds. Therefore, seed size, image contrast, and the visibility of embryo and endosperm structures are important factors affecting the reliability of radiographic imaging for seed viability evaluation.

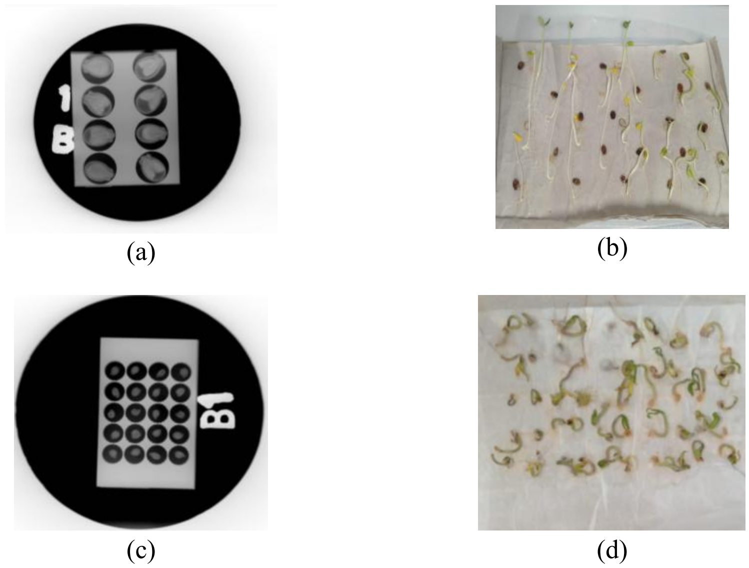


Figure 3. (a) Watermelon seed radiographic image, (b) watermelon conventional germination test, (c) tomato seed radiographic image, (d) tomato conventional germination test

Seed viability can be affected by various internal and external factors. Internal factors include the physiological and biochemical characteristics of seed which depend on the species and are genetically conditioned. Besides that, external factors are influenced by conditions outside the seed, such as humidity and temperature conditions of seed storage (Kijowska-Oberc *et al*., 2021). The germination rate of watermelon seeds indicates the proportion of seeds that successfully germinate under certain conditions. Prajnanta (1996) noted that seedless watermelons exhibit lower germination rates (<75%) than seeded watermelons due to their larger and thicker seeds. To improve germination, it is recommended to crack the seeds to facilitate rapid water absoption.

The data in Table 2 show that Radiographic imaging categorized 607 watermelon seeds as viable and only 1 seed as non-viable, while germination testing identified 560 standard seeds as viable and 48 as non-viable. The 607 viable watermelon seeds represented a combined classification of viable seeds A, B, C, and D. the number of non-viable watermelon seeds identified by the germination test was 48, while only one seed was classified as non-viable by Radiographic analysis. The discrepancy may be due to expert interpretation of Radiographic images, where seeds categorized as viable D showed little endosperm but no visible embryo and were classified as non-viable in the germination test. Seed germination is the process by which important structures develop from the embryo into a plant under suitable conditions (Joshi, 2018), so that without the embryo, the seed cannot germinate. However, radiographic imaging mainly detects physical structure and cannot fully detect physiological or biochemical deterioration; therefore, structurally normal seeds may still fail to germinate. This limitation aligns with the findings of Kim *et al*. (2014), who emphasized that physiological aging and viability loss are linked to altered membrane permeability and moisture absorption, which may not always be reflected solely through structural morphological appearance.

Table 2. Comparison of watermelon and tomato seed viability numbers from Radiographic and conventional germination test

Seed	Radiographic		Germination Test	
	Viable	Non-viable	Viable	Non-viable
Watermelon	607	1	560	48
Tomato	614	86	568	132

For tomato seeds, Radiographics identified 614 viable and 86 non-viable seeds, whereas the germination test identified 568 viable and 132 non-viable seeds. The relatively high number of non-viable tomato seeds is likely due to the small seed size, which can affect the image resolution and increase the difficulty in accurately identifying the completeness of the structure of the seeds, such as the presence or absence of a fully developed embryo and endosperm, using Radiographic images. Image resolution is one of important factor in expert-based identification, as higher resolution images allow clearer visualization of the internal structure of the seeds and improve the accuracy od viability classification. In deep learning models for seed classification, structural image features combined with spatial mappings can be fed into a CNN to automatically learn spatial patterns and reduce human subjectivity during visual grading (Ma *et al*., 2020). False-positive results in tomato seeds indicate that some seeds were classified as viable on radiographic images but failed to produce normal seedlings in the germination test. This suggests that radiographic imaging is effective for structural screening, but germination testing is still needed to confirm physiological viability. These results demonstrate the promising performance of Radiographic imaging compared to conventional gemination testing. Moreover, the Radiographic testing performed did not damage the seed samples.

Table 3. Comparison of Radiographic and Conventional germination test accuracy

Seed	True Positive	True Negative	False Positive	False Negative	Sensitiviy (%)	Accuracy (%)
Watermelon	560	1	47	0	100	92.27
Tomato	568	86	46	0	100	93.43

Table 3 shows the counts of TP, TN, FP, and FN. Watermelon seeds showed a sensitivity level of 100% because there are no viable seeds were classified as non-viable. Moreover, the accuracy rate for watermelon seeds (92.27%) was higher than that for tomato seeds (93.43%). Although tomato had slightly higher numerical accuracy, watermelon radiographic images were easier to interpret visually due to their larger seed size and clearer internal contrast. The effectiveness of using Radiographic technology to detect viable standard seeds was demonstrated. The method's high sensitivity demonstrated its ability to distinguish the majority of viable seeds. The overall accuracy of 92.85% indicates a mixed set of results; this suggests that the model reflects the actual conditions. High classification accuracy demonstrates that imaging-based approaches have considerable potential for rapid seed quality assessment; however, prediction performance remains dependent on the quality of the image data and the characteristics of the evaluated seed species (Jin *et al*., 2022). In other words, the Radiographic test can replace for germination methods for evaluating seed viability. However, the presence of false-positive cases shows that radiographic imaging may overestimate viability when internal morphology appears acceptable but physiological viability has declined. In other words, the radiographic test can be used as a rapid non-destructive screening method, but it should not completely replace germination testing when final confirmation of seed viability is required. Compared with other non-destructive techniques, such as NIR or hyperspectral imasging, radiographic imaging has the advantage of directly showing internal seed structures, although it is limited in detecting physiological damage that is not visible in the image.

4. CONCLUSION

Industrial radiographic imaging shows potential as a non-destructive screening method for evaluating the viability of watermelon and tomato seeds by assessing their internal structural integrity. In this study, the method achieved 100% sensitivity for both seed types, with an accuracy of 92.27% for watermelon seeds and 93.43% for tomato seeds. The use of an X-ray generator and scanner enabled visualization of key internal seed structures, including embryo and endosperm completeness, which was validated against conventional germination testing. However, seed size and internal morphology influenced image interpretation. The smaller size and more compact internal structure of tomato seeds may increase interpretation uncertainty, indicating the need to optimize radiographic parameters and grading criteria, particularly for small-seeded crops. These results suggest that radiographic imaging can facilitate rapid pre-screening of seed lots, especially for identifying structurally empty or severely damaged seeds. Nevertheless, because radiographic images primarily provide structural information and do not directly assess physiological activity, this method should be complemented by germination testing to confirm final viability. Future research should focus on developing automated classification models to improve accuracy, reproducibility, and objectivity, while reducing subjectivity and reliance on manual expert interpretation.

AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Rad	✓					✓		✓	✓			✓		
AH		✓	✓	✓				✓	✓	✓	✓	✓		
MAFF	✓					✓		✓	✓		✓	✓		
ABS	✓	✓				✓		✓	✓	✓	✓	✓		
Sol		✓		✓	✓			✓		✓	✓			
LA		✓	✓	✓	✓	✓		✓	✓	✓	✓			
GHJ				✓	✓	✓		✓	✓	✓	✓			
HHH		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	
ATI				✓	✓	✓		✓	✓	✓			✓	
ANP									✓	✓			✓	
MAP		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	
NF		✓				✓								✓
BH		✓				✓	✓							

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

ACKNOWLEDGMENTS

This research was funded by the Indonesian Endowment Fund for Education (LPDP) through the *Making Indonesia 4.0* Program under the RISPRO Invitational Research Grant scheme awarded by PT East West Seed Indonesia to Universitas Gadjah Mada (Contract No. PRJ-2/LPDP/LPDP.4/2023). The authors gratefully acknowledge the support of the NDT Advanced Radiology Laboratory, National Research and Innovation Agency (BRIN) for providing access to advanced radiographic facilities and technical assistance for seed radiographic image acquisition. The authors also express their sincere appreciation to all collaborating partners for their valuable contributions and collaborative efforts in advancing science and technology, particularly in the development of innovative seed viability measurement and sorting technologies to address the needs of the seed industry.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

During the preparation of this work the authors used ScopusAI and SCISPCE in order to collect the related references. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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