

Article

Seed Germination Analysis Based on Raman Spectroscopy

Shupeng Liu ¹, Han Wang ¹, Jing Tian ^{2,*}, Na Chen ¹ , Yana Shang ¹, Jian Zhang ¹ and Heng Zhang ^{1,*}

¹ Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, 333 Nanchen Road, Shanghai 200444, China; liusp@shu.edu.cn (S.L.); wanghan12138@shu.edu.cn (H.W.); na.chen@shu.edu.cn (N.C.); ynshang@shu.edu.cn (Y.S.); jianzhang@shu.edu.cn (J.Z.)

² School of Electron and Computer, Southeast University Chengxian College, Nanjing 210088, China

* Correspondence: jingtian@cxy.seu.edu.cn (J.T.); zhanghg@shu.edu.cn (H.Z.)

Abstract: Surface-enhanced Raman spectroscopy was employed to measure lettuce seeds at five different germination stages. Experimental results show that 85% of the spectra of normally germinating seeds exhibited consistency in both peak positions and quantities at the same germination stage, while spectra from seeds that failed to germinate normally demonstrated significant differences compared to normal ones. These data indicate that the surface-enhanced Raman spectrum of seeds could serve as an effective method for detecting seed germination rates.

Keywords: surface-enhanced Raman spectroscopy; lettuce seed; germination rate

1. Introduction

Raman spectroscopy is an inelastic light-scattering technique. Its main principle is that the incident photon interacts with the sample to produce scattered photons of different wavelengths than the incident photons in the Raman scattering process [1]. Raman spectroscopy contains a wealth of information that can be applied to chemical identification [2], molecular structure characterization, bonding effects, and the environment in which the sample is located, as well as the internal stress distribution. In recent years, Raman spectroscopy has become one of the main methods for molecular structure research due to its unique advantages, such as rapidity, high precision, and non-invasiveness [3–5]. Therefore, it is widely used in the fields of plant physiology [6], food safety [7], tumor detection [8], environmental detection and pollution control. R Baranski et al. demonstrated the special potential of Raman spectroscopy for the studying selected plant metabolites [9]. Ciallamay et al. reviewed the application of surface-enhanced Raman spectroscopy (SERS) in biological and biomedical detection schemes [10].

At the same time, the seed germination process is an important foundation for plant growth. Studying the germination stages of seeds will benefit the plant growth process [11,12]. Good seeds are the key to agriculture, and seed quality measurement is the backbone of agricultural practice [13]. Currently, the main research focus is to obtain reference measurements to evaluate seed quality and further plan and forecast profitable crop yields [14–17]. Li et al. proposed a rapid and non-invasive method to measure the germination rate of hybrid rice seeds based on near-infrared reflectance spectroscopy [18]. Ambrose et al. combined partial least squares discriminant analysis with Raman and infrared spectroscopy and assessed the viability of maize seeds with an accuracy rate of 95% [19]. Recently, de Melo Bessa et al. (2024) demonstrated the application of organic–inorganic hybrid materials as coating membranes to enhance white rot control in garlic



Academic Editors: Clemens Burda and Monica Baia

Received: 17 January 2025

Revised: 2 March 2025

Accepted: 29 May 2025

Published: 6 June 2025

Corrected: 28 May 2026

Citation: Liu, S.; Wang, H.; Tian, J.; Chen, N.; Shang, Y.; Zhang, J.; Zhang, H. Seed Germination Analysis Based on Raman Spectroscopy. *Spectrosc. J.* **2025**, *3*, 19. <https://doi.org/10.3390/spectroscj3020019>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

bulbils, thereby highlighting the potential of advanced materials in improving agricultural practices [20].

In this paper, we obtained the Raman spectra at each stage of seed germination through experiments and further analyzed the corresponding Raman spectral peaks in combination with the physiological and biochemical changes during germination. In general, we provide a new method for the rapid detection of seed germination rates.

2. Materials and Methods

The Raman spectrometer used in the experiment was LabRAM HR Evolution (HORIBA France SAS), a confocal Raman spectrometer from HORIBA Science. During the experiment, a 633 nm light source, 50% laser power (about 2.5 mW), and a 50× magnification objective lens were used. The raw data points were recorded according to the actual measured Raman shift values, rather than at fixed intervals, with the minimum difference between adjacent Raman shift values being 0.82 cm^{-1} , which represents the spectral resolution. The spectrometer was configured with a 600 lines per millimeter (lpm) grating, which ensured optimal spectral resolution within the targeted wavelength range. The data acquisition range was $500\text{--}1700\text{ cm}^{-1}$. Gold sol was used as a Raman spectroscopy measurement enhancement agent during the experiment. The selected seeds for this experiment were lettuce seeds purchased from the Changfeng Seed Industry (Shanghai, China), and the germination rate of over 85%. Because the germination cycle of the lettuce seed is short—they sprout in about 24 h under normal conditions—the selection of the lettuce seeds allows for the rapid acquisition of samples at different stages. The term “white” here refers to seeds that have just broken through the seed coat.

Preparation of Gold Sol Solution: Gold sol was prepared using the sodium citrate reduction method. Briefly, 1 g of chloroauric acid (HAuCl_4) was dissolved in 99 mL of deionized water to form a 1% (w/v) solution. Separately, 1 g of sodium citrate was dissolved in 99 mL of deionized water to form a 1% (w/v) solution. The chloroauric acid solution was heated to boiling under microwave irradiation, and 0.8 mL of sodium citrate solution was added. The mixture was cooled to room temperature, yielding a wine-red gold sol indicative of gold nanoparticle formation.

(a) The purchased oilseed rapeseed seeds were divided into 5 groups of 30 seeds each, numbered as seed1, seed2, seed3, seed4 and seed5, respectively.

(b) The five groups were placed in warm water at $25\text{ }^{\circ}\text{C}$, seed1 for 0 h, seed2 for 6 h, seed3 for 12 h, seed4 for 18 h, and seed5 for 24 h.

(c) After soaking, the seeds were manually shelled using tweezers and then finely mashed to achieve a uniform consistency. The processed seed material was then transferred into a centrifuge tube, where a gold sol solution was added and thoroughly mixed to form a homogeneous suspension. This suspension was subsequently pipetted onto a silicon wafer for Raman spectroscopy analysis.

(d) Finally, Raman spectroscopy measurements were performed on the seeds of the five different soaking periods. Each group of 30 seeds was measured individually, with three measurements taken per seed. The data from the three measurements were averaged to obtain the mean spectra, resulting in 150 sets of experimental data. All raw Raman spectra acquisitions were performed with LabSpec software (HORIBA France SAS). The baselines of raw data were corrected by Subase V2.10 software (selfdeveloped, HyStudio, Shanghai University, China) with integration of a Vancouver Raman Algorithm based on fifth-order polynomial fitting method for fluorescence background removal. To investigate the germination process of seeds, we monitored their morphological changes, including the rupture of the seed coat and the emergence of the radicle. Additionally, a microscope was employed to examine the detailed structures of seeds at various stages of germina-

tion. Seed germination is a complex physiological process characterized by significant biochemical transformations. Raman spectroscopy serves as a powerful tool to capture these changes by identifying key chemical constituents within seeds. Throughout the germination process, seeds undergo hydration, membrane repair, nutrient metabolism, and biomolecule synthesis, all of which can be effectively monitored through characteristic Raman spectral peaks.

3. Results and Discussions

Because the germination rate of the experimental sample seeds is greater than or equal to 85%, when measuring the seeds at these five stages, we obtained two different types of data in each stage: one for seeds that can germinate normally and the other for seeds that cannot germinate normally. The data with higher frequency of the same type can be considered as the data of normal germinating seeds, and the other type is the seeds that cannot be normally germinated. These observations align with prior research on the effects of thiamethoxam on the photosynthetic apparatus of maize leaves, which documented substantial biochemical alterations [21].

Due to the large number of original images, this presentation will only showcase the raw Raman spectrum of a normal seed sample labeled as Seed No. 1 during its second Raman detection at the 24 h mark (Figure 1). Additionally, Figure 2 includes the Raman spectrum after applying basic baseline correction and smoothing procedures (not the final result, as each seed requires repeated observations and the results should be averaged for final analysis).

The 30 seeds soaked for 0 h were measured first. The data after three measurements was averaged into one spectral data. After testing all 30 seeds, they were divided into two categories. A total of 28 sets of spectral data show the same number and peak positions, classified as normal seeds, while the two datasets in the second category showed different peak positions, classified as abnormal seeds. The data of the first type were then averaged to obtain the mean Raman spectrum of normal seeds after 0 h of soaking (Figure 3). The comparison between the normal group and the abnormal group is shown in Figure 4.

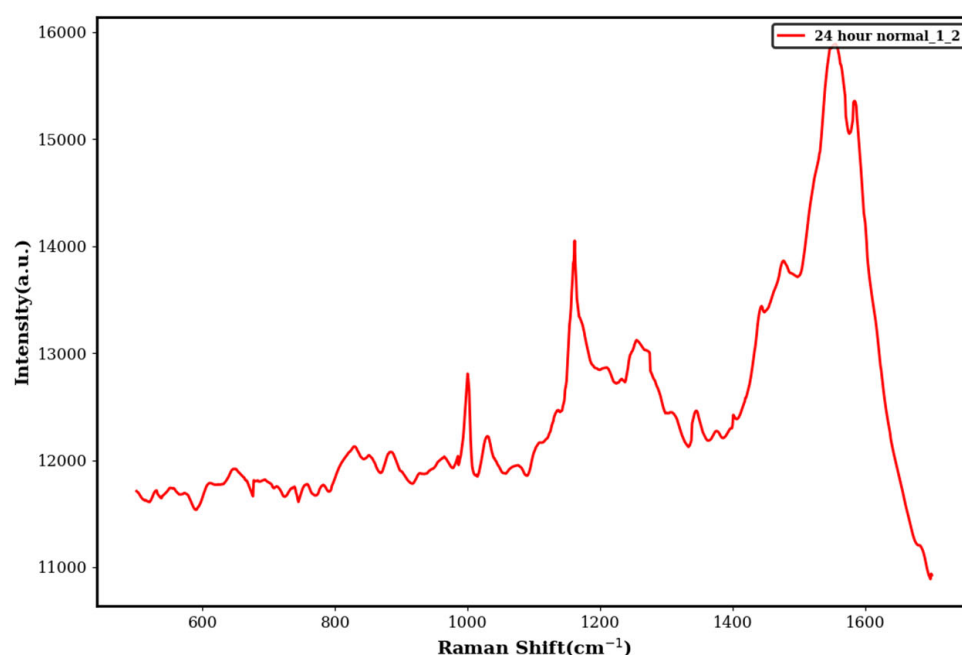


Figure 1. The Raman spectrum corresponding to the second observation of Seed No. 1 after a 24 h soak under normal conditions.

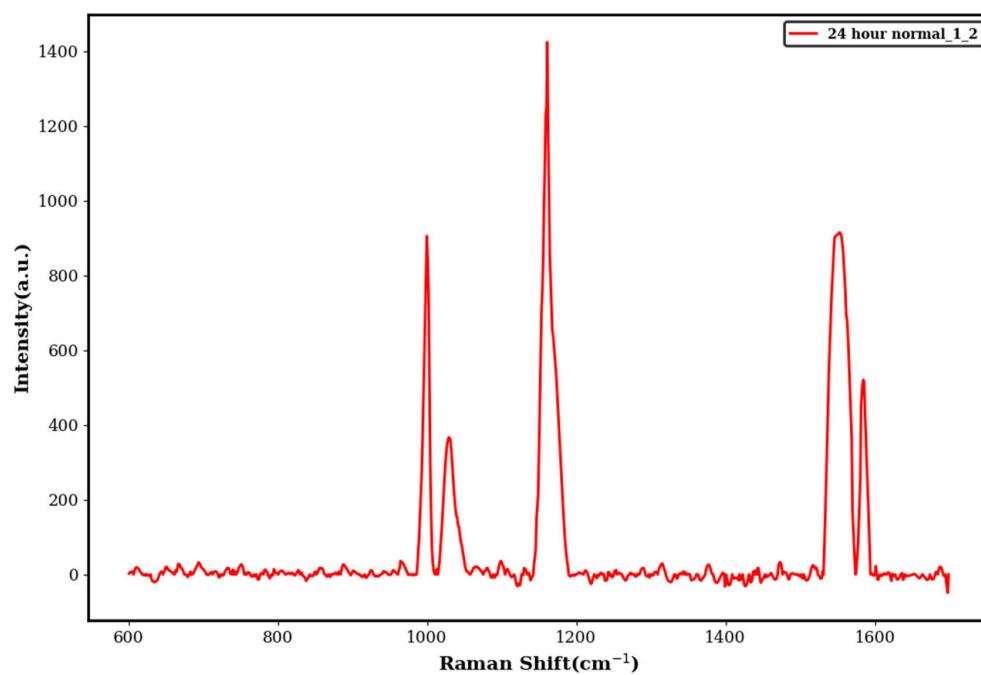


Figure 2. The Raman spectrum that has undergone basic baseline correction and smoothing processing based on Figure 1.

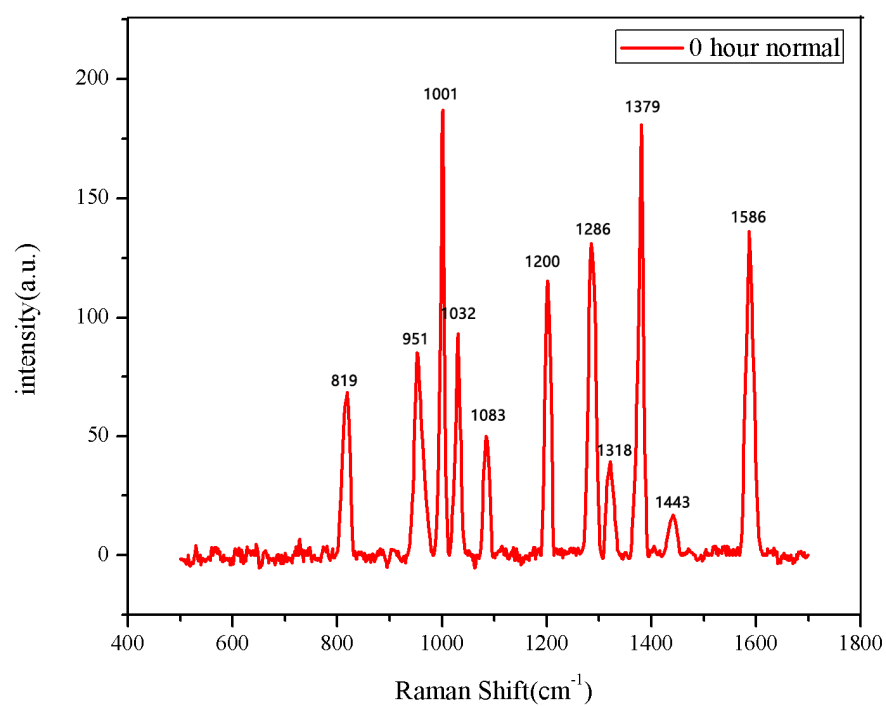


Figure 3. The average Raman spectrum of normal seeds soaked for 0 h.

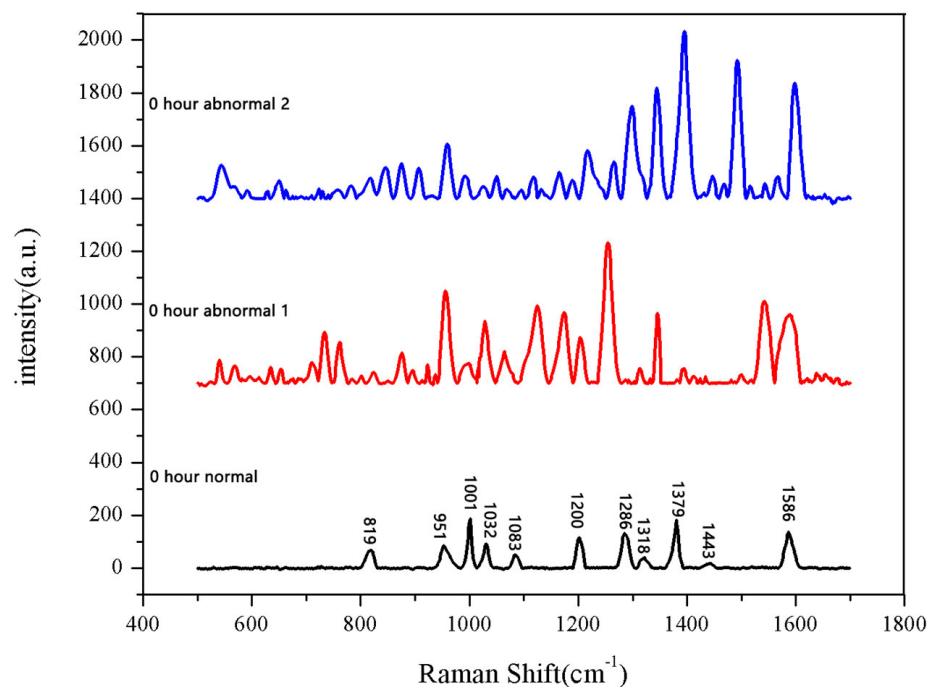


Figure 4. Comparison between normal and non-normal groups soaked for 0 h.

The same method was used to measure the seeds soaked for 6 h, 12 h, 18 h and 24 h (Figures 5, 7, 9 and 11). For the 6 h group, 26 datasets were classified as normal seeds and 4 as abnormal seeds; for the 12 h group, 26 datasets were normal and 4 were abnormal; for the 18 h group, 28 datasets were normal and 2 were abnormal. The Raman spectra of the normal and abnormal groups are shown in Figures 6, 8 and 10.

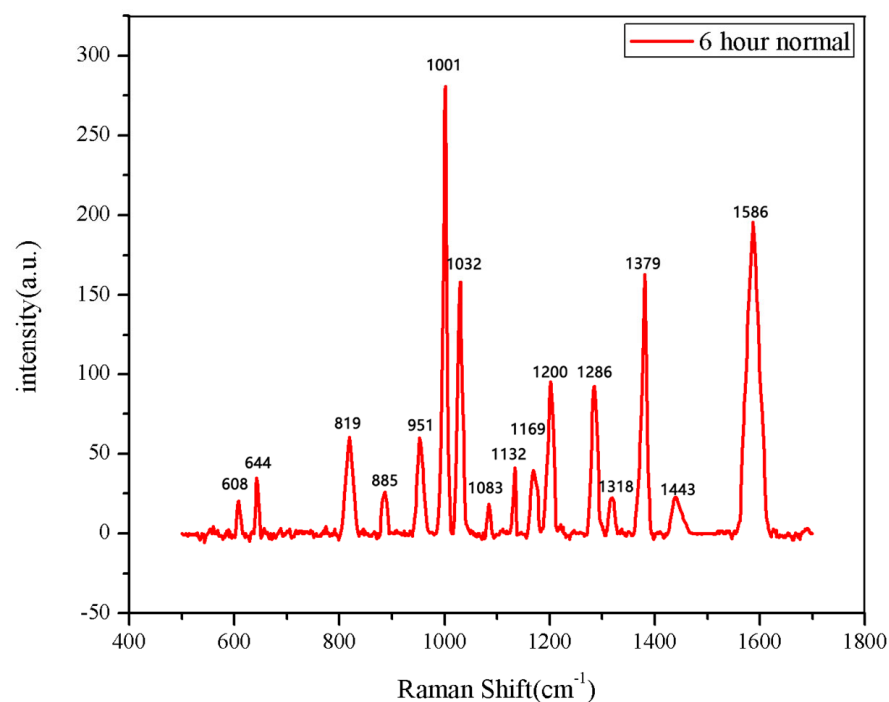


Figure 5. The average Raman spectrum of normal seeds soaked for 6 h.

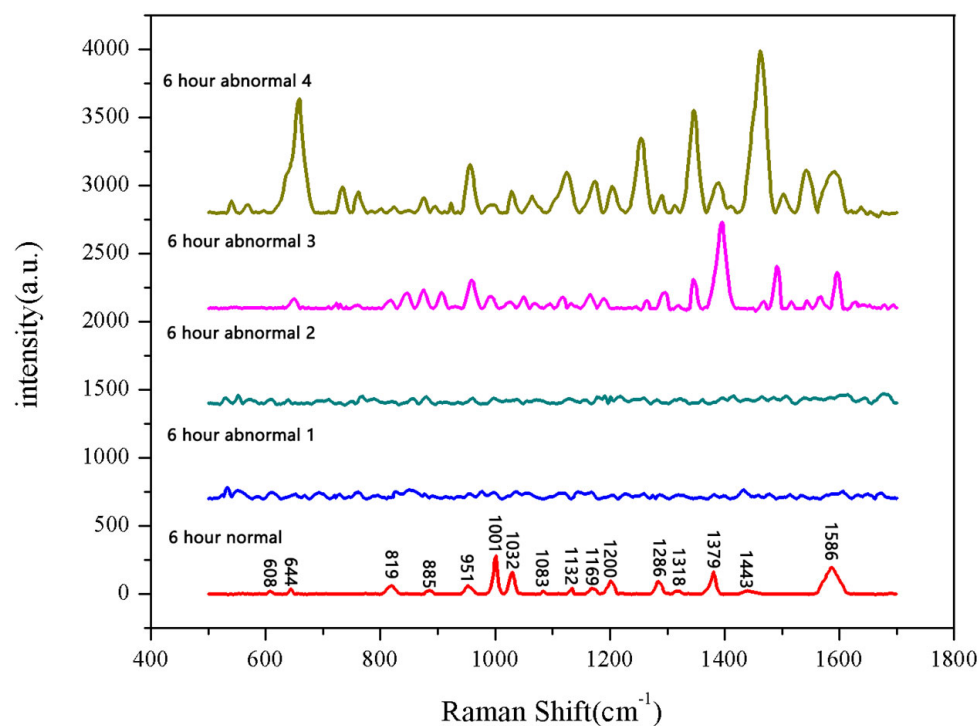


Figure 6. Comparison between normal and non-normal groups soaked for 6 h.

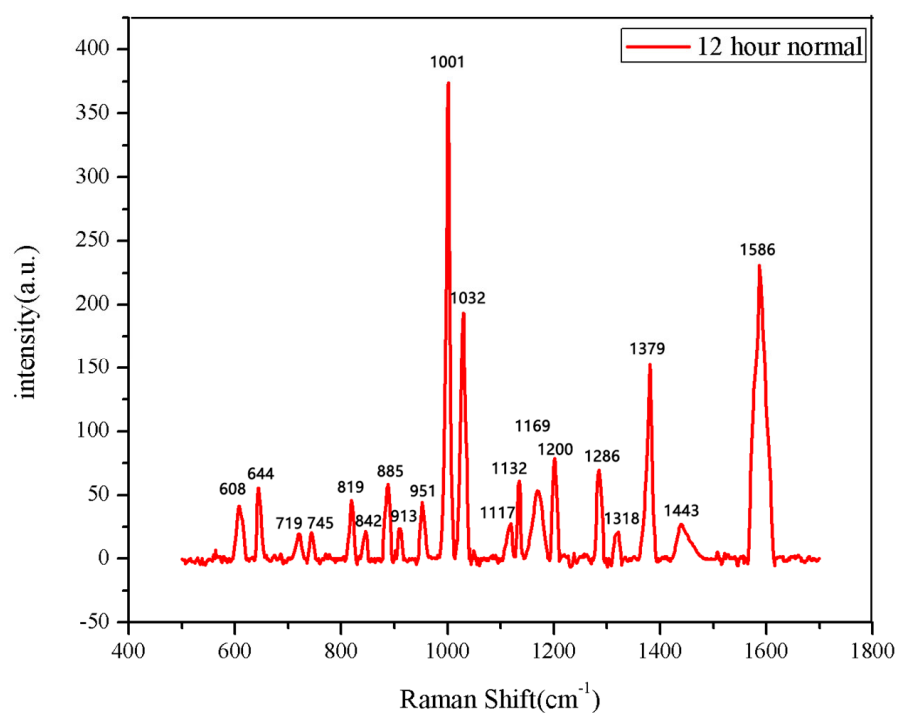


Figure 7. The average Raman spectrum of normal seeds soaked for 12 h.

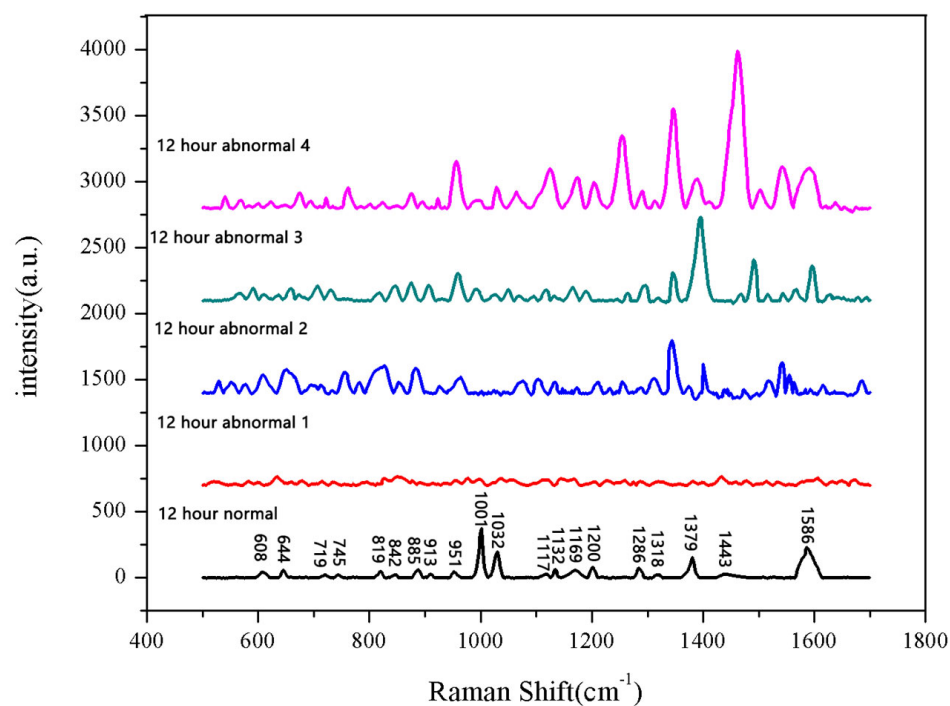


Figure 8. Comparison of Raman spectra between normal and non-normal groups soaked for 12 h.

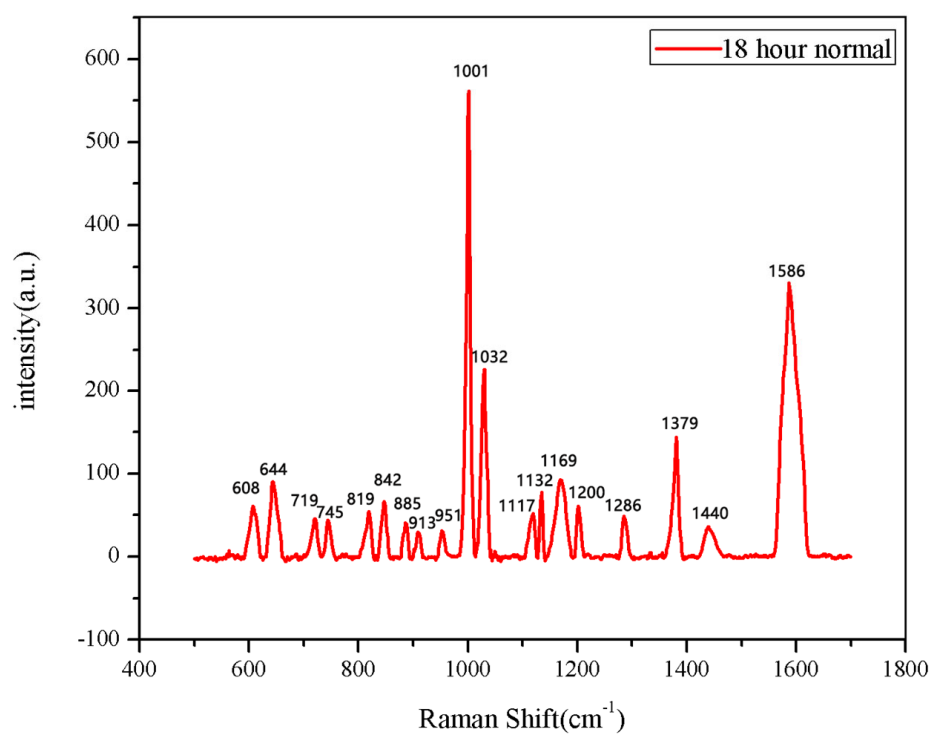


Figure 9. The average Raman spectrum of normal seeds soaked for 18 h.

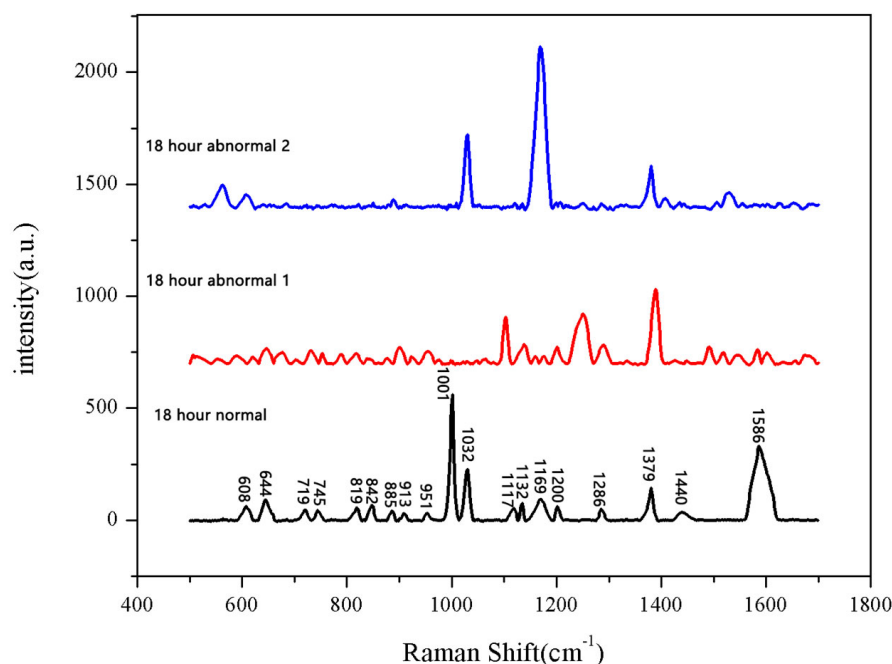


Figure 10. Comparison of Raman spectra between normal and abnormal groups soaked for 18 h.

The seeds soaked for 24 h were measured. Among the 30 seeds, 28 seeds had sprouted, while the other 2 had not. We measured both the sprouted and unsprouted seeds. The Raman spectra of the sprouted seeds showed the same peak positions and numbers, whereas the spectra of the two unsprouted seeds were different from those of the sprouted seeds. We averaged the data of normal sprouted and unsprouted seeds. The comparison of Raman spectra between normal sprouted and unsprouted seeds is shown in Figure 12.

To facilitate the analysis of these spectral features, the detailed peak assignments are provided in Table 1.

Table 1. Tentative Assignment Table for Seed SERS Characteristic Peaks (Informed by the existing body of reference literature [1,6,9]).

Peak Position/cm ⁻¹	Major Assignments
608	Glycerol
644	Tyrosine
719	DNA
745	Ring breathing mode of RNA bases
819	Proteins
842	Glucose
885	Disaccharide
913	Glucose
951	Proteins
1001	Phenylalanine
1032	Phospholipids
1083	Proteins
1117	Glucose
1132	Fatty acid
1169	Tyrosine
1200	Amide III (proteins)
1286	Cytosine
1318	Guanine
1379	lipid assignment
1443	Fatty acids
1586	Phenylalanine

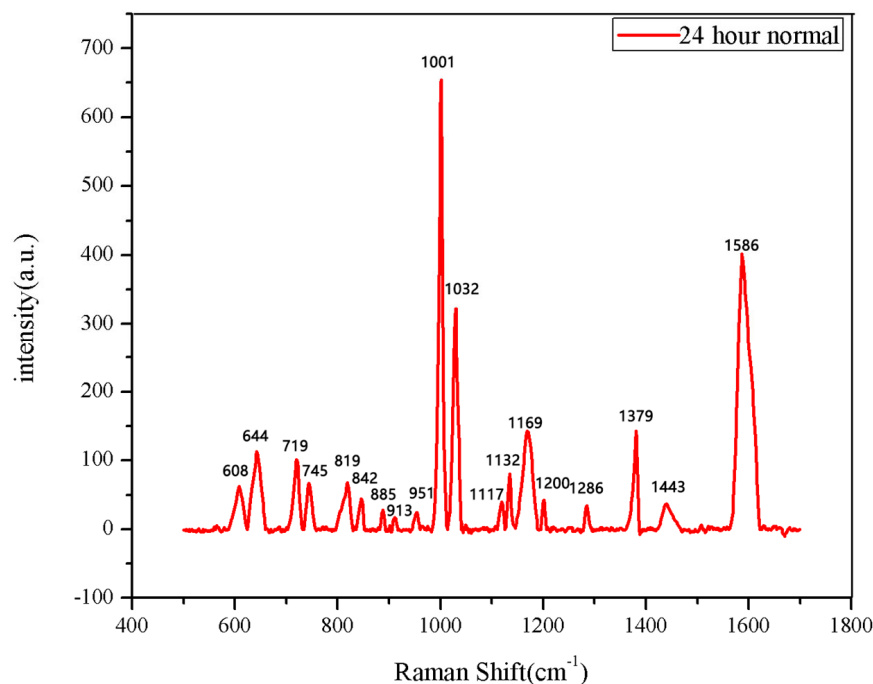


Figure 11. The average Raman spectrum of normal seeds soaked for 24 h.

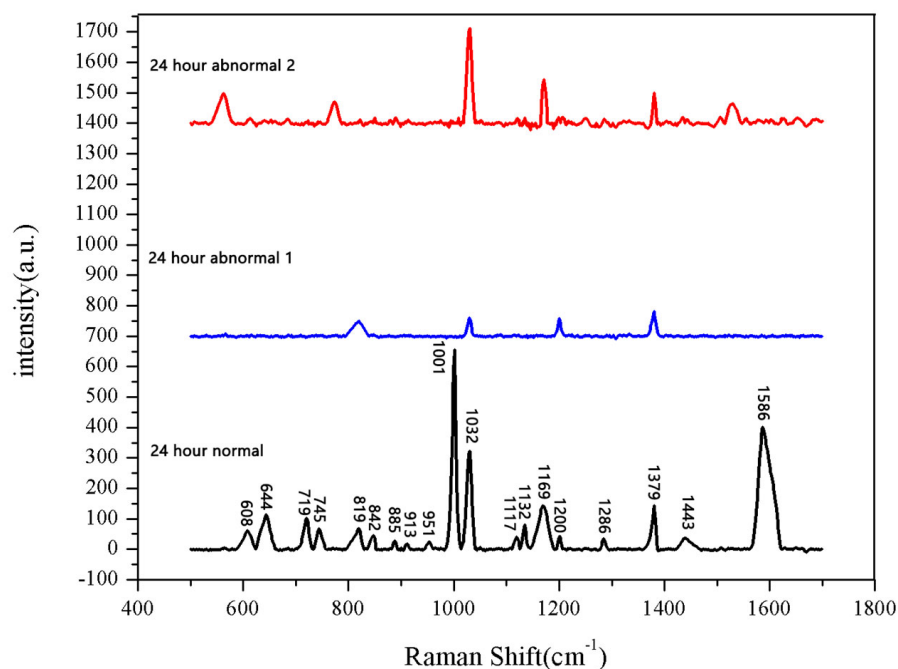


Figure 12. Comparison of Raman spectra of sprouted seeds and unsprouted seeds after soaking for 24 h.

According to Figure 13, the Raman spectra of seeds measured at 0 h exhibited distinct peaks at 819, 951, 1001, 1032, 1083, 1200, 1286, 1318, 1379, and 1586 cm^{-1} . The Raman spectra of seeds measured at 6 h showed distinct peaks at 608, 644, 819, 885, 951, 1001, 1032, 1083, 1169, 1200, 1286, 1318, 1379, 1443, and 1586 cm^{-1} . Compared with the data at 0 h, there were additional peaks at 608, 644, 885, 1169, and 1443 cm^{-1} . The peak positions at 819, 951, 1083, 1200, 1286, 1318, and 1379 cm^{-1} showed a decrease, while those at 1001, 1032, 1443, and 1586 cm^{-1} showed an increase. The substances corresponding to the additional peak positions were classified as glycerol (608 cm^{-1}), tyrosine (644 cm^{-1} , 1169 cm^{-1}), disaccharide (885 cm^{-1}), and fatty acid (1443 cm^{-1}). The substances corresponding to

the decreased peak positions were classified as proteins (819 cm^{-1} , 951 cm^{-1} , 1083 cm^{-1} , 1200 cm^{-1}), cytosine (1286 cm^{-1}), guanine (1318 cm^{-1}), and fat (1379 cm^{-1}). The substances corresponding to the increased peak positions were classified as phenylalanine (1001 cm^{-1} , 1586 cm^{-1}), phospholipid (1032 cm^{-1}), and fatty acid (1443 cm^{-1}). These data indicate that from 0 to 6 h, the dry seeds absorbed water and gradually began to repair the cell membrane, and the substances in the seeds started to activate. Various amino acids, fatty acids, and glycerol began to appear or increase due to the decomposition of proteins, fats, and starches.

The Raman spectrum of seeds soaked for 12 h showed distinct peaks at 608, 644, 719, 745, 819, 842, 885, 913, 951, 1001, 1032, 1117, 1132, 1169, 1200, 1286, 1318, 1379, 1443, and 1586 cm^{-1} . Compared with the data measured at 6 h, there were additional peaks at 719, 745, 842, 913, and 1117 cm^{-1} . The peak positions at 608, 644, 885, 1001, 1032, 1132, 1169, and 1586 cm^{-1} showed an increase, while those at 819, 951, 1083, 1200, 1286, 1318, and 1379 cm^{-1} showed a decrease. The substances corresponding to the additional peak positions belonged to DNA (719 cm^{-1}), RNA (745 cm^{-1}), and glucose (842 cm^{-1} , 913 cm^{-1} , 1117 cm^{-1}). The substances corresponding to the increased peak positions belonged to glycerol (608 cm^{-1}), tyrosine (644 cm^{-1} , 1169 cm^{-1}), disaccharide (885 cm^{-1}), phenylalanine (1001 cm^{-1} , 1586 cm^{-1}), phospholipid (1032 cm^{-1}), and fatty acid (1132 cm^{-1}). The substances corresponding to the decreased peak positions belonged to proteins (819 cm^{-1} , 951 cm^{-1} , 1083 cm^{-1} , 1200 cm^{-1}), cytosine (1286 cm^{-1}), guanine (1318 cm^{-1}), and fat (1379 cm^{-1}). The data indicate that from 6 to 12 h, the disaccharides were gradually decomposed into monosaccharides, and the contents of various amino acids, glycerol, and fatty acids gradually increased due to the decomposition of proteins and fats.

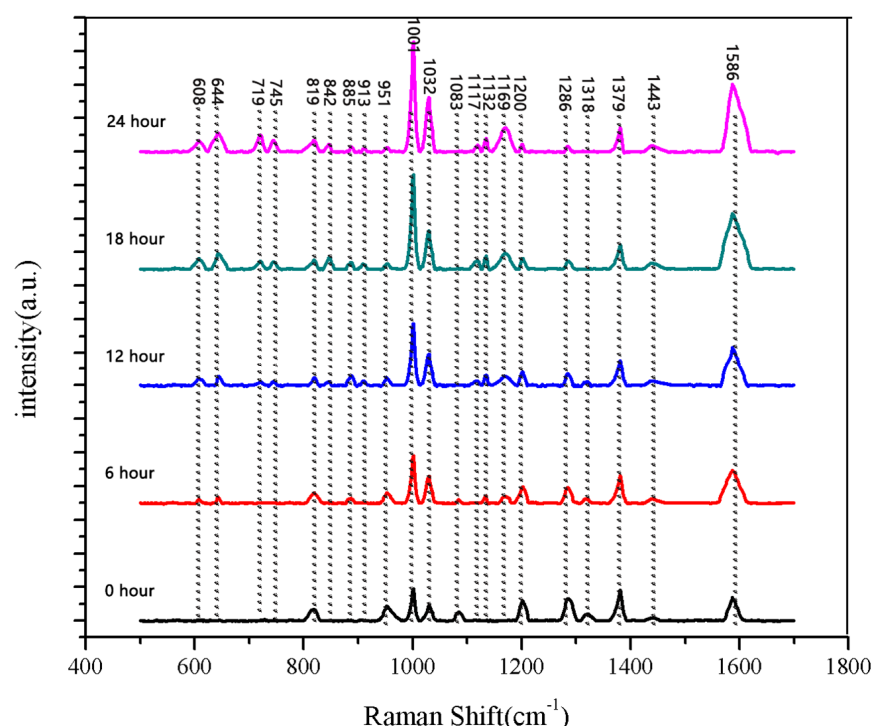


Figure 13. Comparison of average Raman spectra of normal seeds at five different soaking stages.

The Raman spectrum of seeds soaked for 18 h showed distinct peaks at 608, 644, 719, 745, 819, 842, 885, 913, 951, 1001, 1032, 1117, 1132, 1169, 1200, 1286, 1318, 1379, 1440, and 1586 cm^{-1} . Compared with the data measured at 12 h, there were no additional peaks. The peak positions at 608, 644, 719, 745, 842, 913, 1001, 1032, 1117, 1132, 1169, 1443, and

1586 cm^{-1} showed an increase, while those at 819, 885, 951, 1200, 1286, 1318, and 1379 cm^{-1} showed a decrease. The substances corresponding to the increased peak positions belonged to glycerol (608 cm^{-1}), tyrosine (644 cm^{-1} , 1169 cm^{-1}), DNA (719 cm^{-1}), RNA (745 cm^{-1}), glucose (842 cm^{-1} , 913 cm^{-1} , 1117 cm^{-1}), fatty acid (1132 cm^{-1}), and phenylalanine (1001 cm^{-1} , 1586 cm^{-1}). The substances corresponding to the decreased peak positions belonged to disaccharide (885 cm^{-1}), proteins (819 cm^{-1} , 951 cm^{-1} , 1083 cm^{-1} , 1200 cm^{-1}), cytosine (1286 cm^{-1}), guanine (1318 cm^{-1}), and fat (1379 cm^{-1}). The data indicate that between 12 and 18 h, the DNA and RNA molecules in the seeds were continuously repaired, and proteins, disaccharides, and fats were being continuously consumed.

The Raman spectrum of seeds soaked for 24 h showed distinct peaks at 608, 644, 719, 745, 819, 842, 885, 913, 951, 1001, 1032, 1117, 1132, 1169, 1200, 1286, 1318, 1379, 1440, and 1586 cm^{-1} . Compared with the seeds measured at 18 h, there was no increase or decrease in the peaks. The peak positions at 608, 644, 719, 745, 1001, 1032, 1132, 1169, and 1586 cm^{-1} showed an increase, while those at 842, 885, 913, 1117, 1200, 1286, and 1379 cm^{-1} showed a significant decrease. The substances corresponding to the increased peak positions belonged to glycerol (608 cm^{-1}), tyrosine (644 cm^{-1} , 1169 cm^{-1}), DNA (719 cm^{-1}), RNA (745 cm^{-1}), fatty acid (1132 cm^{-1}), and phenylalanine (1001 cm^{-1} , 1586 cm^{-1}). The substances corresponding to the decreased peak positions belonged to glucose (842 cm^{-1} , 913 cm^{-1} , 1117 cm^{-1}), disaccharide (885 cm^{-1}), cytosine (1286 cm^{-1}), and fat (1379 cm^{-1}). The data indicate that between 18 and 24 h, the seeds continuously synthesized genetic materials and consumed more carbohydrates.

4. Conclusions

The findings of this study underscore the potential of Raman spectroscopy as a robust and reliable tool for analyzing seed germination stages and detecting germination rates. The consistent spectral patterns observed in normal seeds, coupled with the significant differences identified in abnormal seeds, offer a solid foundation for rapid and non-invasive seed quality assessment. Future research endeavors should aim to broaden the spectrum of seed varieties subjected to testing and refine spectral analysis methodologies. Such advancements will further enhance the accuracy and applicability of Raman spectroscopy in seed quality evaluation, thereby contributing to more efficient and precise agricultural practices.

This study employed Raman spectroscopy to evaluate seed germination stages and detect germination rates. Normal seeds exhibited characteristic Raman bands (e.g., according to Table 1, 819 cm^{-1} for proteins, 1001 cm^{-1} and 1586 cm^{-1} for phenylalanine), which were either absent or significantly diminished in abnormal seeds. These observations suggest that the presence of specific amino acids and proteins is critical for successful germination, findings that are consistent with previous research on seed germination and Raman spectroscopy.

In this study, surface-enhanced Raman spectroscopy (SERS) was used to provide a detailed analysis of biochemical markers. By identifying specific Raman bands associated with normal and abnormal germination, our approach enhances the precision of seed quality assessment.

The findings have significant implications for agricultural applications. Raman spectroscopy offers a rapid and non-invasive method for evaluating seed quality, which has the potential to increase crop yields and reduce costs. Future research should focus on expanding the range of seed varieties tested and refining spectral analysis methodologies to further improve the accuracy and applicability of this technique.

In conclusion, this study demonstrates the potential of Raman spectroscopy as a powerful tool for seed quality assessment and contributes to the growing body of literature on its agricultural applications.

Author Contributions: Conceptualization, J.T., S.L. and H.Z.; methodology, N.C., S.L. and Y.S.; software, H.Z.; validation, J.Z., H.W., and H.Z.; investigation, S.L. and H.Z.; resources, J.Z. and J.T.; writing—original draft preparation, J.Z. and H.W.; writing—review and editing, J.T. and N.C.; supervision, H.Z. and J.T.; project administration, S.L.; funding acquisition, Y.S. and N.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the National Natural Science Foundation of China (Project Nos: U24A20321 and 62175142).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Lewis, E.N.; Qi, W.; Kidder, L.H.; Amin, S.; Kenyon, S.M.; Blake, S. Combined dynamic light scattering and Raman spectroscopy approach for characterizing the aggregation of therapeutic proteins. *Molecules* **2014**, *19*, 20888–20905. [\[CrossRef\]](#)
- Si, G.; Wang, Y.; Liu, X.; Sun, C.; Miao, J.; Li, Z. Detection of powder samples based on UV Raman—Fluorescence spectroscopy. *Opt. Commun.* **2024**, *571*, 130950. [\[CrossRef\]](#)
- Xu, M.L.; Gao, Y.; Han, X.X. Structure information analysis and relative content determination of protein and chitin from yellow mealworm larvae using Raman spectroscopy. *Int. J. Biol. Macromol.* **2024**, *272*, 132787. [\[CrossRef\]](#)
- Lin, M.; Guan, J.; Diop, M.A.; Zhao, X.; Ma, S.; Li, Y.; Chen, P. Unveiling ionic structure in the LiF-NdF₃ molten salt system as determined by Raman spectroscopy and quantum chemical calculations. *J. Mol. Liq.* **2024**, *400*, 124602. [\[CrossRef\]](#)
- Fukue, H.; Nakatani, T.; Takabayashi, S.; Okano, T.; Kuroiwa, M.; Kunitsugu, S.; Oota, H.; Yonezawa, K. Raman spectroscopy analysis of the chemical structure of diamond-like carbon films deposited via high-frequency inclusion high-power impulse magnetron sputtering. *Diam. Relat. Mater.* **2024**, *142*, 110768. [\[CrossRef\]](#)
- Khan, U.M.; Sameen, A.; Decker, E.A.; Shabbir, M.A.; Hussain, S.; Latif, A.; Abdi, G.; Aadil, R.M. Implementation of plant extracts for cheddar-type cheese production in conjunction with FTIR and Raman spectroscopy comparison. *Food Chem.* **2024**, *22*, 101256. [\[CrossRef\]](#) [\[PubMed\]](#)
- Maurizi, L.; Iordachescu, L.; Kirstein, I.V.; Nielsen, A.H.; Vollertsen, J. Do drinking water plants retain microplastics? An exploratory study using Raman micro-spectroscopy. *Heliyon* **2023**, *9*, 2405–8440. [\[CrossRef\]](#) [\[PubMed\]](#)
- Esteves, B.; Pimenta, S.; Maciel, M.J.; Costa, M.; Baltazar, F.; Cerqueira, M.F.; Alpuim, P.; Silva, C.A.; Correia, J.H. Raman spectroscopy for classification of neoplastic and non-neoplastic CAM colon tumors. *Heliyon* **2024**, *10*, 2405–8440. [\[CrossRef\]](#)
- Baranska, M.; Roman, M.; Dobrowolski, J.C.; Schulz, H.; Baranski, R. Recent advances in Raman analysis of plants: Alkaloids, carotenoids, and polyacetylenes. *Curr. Anal. Chem.* **2013**, *9*, 108–127. [\[CrossRef\]](#)
- Cialla-May, D.; Zheng, X.S.; Weber, K.; Popp, J. Recent progress in surface-enhanced Raman spectroscopy for biological and biomedical applications: From cells to clinics. *Chem. Soc. Rev.* **2017**, *46*, 3945–3961. [\[CrossRef\]](#)
- Wang, X.; Wang, A.; Zhuang, M.; Ke, S.; Ning, M.; Zhou, Z. Impact of metabolites derived from *Bacillus velezensis* on the germination of tigernut seeds and the underlying molecular regulatory mechanism. *Food Biosci.* **2024**, *62*, 105169. [\[CrossRef\]](#)
- Mohajer, M.H.; Monfaredi, M.; Rahmani, M.; Martami, M.; Razaghiha, E.; Mirjalili, M.H.; Hamidi, A.; Ghomi, H.R. Impact of dielectric barrier discharge plasma and plasma-activated water on cotton seed germination and seedling growth. *Heliyon* **2024**, *10*, 2405–8440. [\[CrossRef\]](#)
- Sivachandiran, L.; Khacef, A. Enhanced seed germination and plant growth by atmospheric pressure cold air plasma: Combined effect of seed and water treatment. *RSC Adv.* **2017**, *7*, 1822–1832. [\[CrossRef\]](#)
- Ng, J.; Liao, I.Y.; Jelani, M.F.; Chen, Z.Y.; Wong, C.K.; Wong, W.C. Multiview-based method for high-throughput quality classification of germinated oil palm seeds. *Comput. Electron. Agric.* **2024**, *218*, 108684. [\[CrossRef\]](#)
- Rondan, W.; dos Reis, R.A.; Acuña, J.J.S.; Seabra, A.B.; Champi, A. Influence of multilayers Bernal and Rhombohedral graphene obtained by green chemistry on the acceleration in the germination process of tomato seeds. *Diam. Relat. Mater.* **2024**, *145*, 111077. [\[CrossRef\]](#)
- Survase, A.A.; Kanase, S.S. Novel microbial synthesis of rGO nanosheets for effective photocatalytic remediation of Acid Blue 113 dye, improved seed germination, antimicrobial and antioxidant applications. *J. Mol. Struct.* **2024**, *1302*, 137421. [\[CrossRef\]](#)
- Weishaar, C.E.; Phippen, W.B. Indigo (*Indigo suffruticosa* Mill.) seed germination to improve commercial viability. *Ind. Crops Prod.* **2024**, *221*, 119347. [\[CrossRef\]](#)

18. Li, Y.N.; Jiang, D.; Liu, Y.Y.; Ding, W.M.; Ding, Q.S.; Zha, L.Y. Testing of germination rate of hybrid rice seeds based on near-infrared reflectance spectroscopy. *Spectrosc. Spectr. Anal.* **2014**, *34*, 1528.
19. Ambrose, A.; Lohumi, S.; Lee, W.H.; Cho, B.K. Comparative nondestructive measurement of corn seed viability using Fourier transform near-infrared (FT-NIR) and Raman spectroscopy. *Sens. Actuators B Chem.* **2016**, *224*, 500–506. [[CrossRef](#)]
20. de Melo Bessa, L.A.; Nazário, M.L.F.; Izumi, C.M.S.; Constantino, V.R.L.; Lourenço, V.; Lopes, E.A.; Mizubuti, E.S.G.; Tronto, J. Enhanced white rot control in garlic bulbil using organic–inorganic hybrid materials as coating membranes. *Dalton Trans.* **2024**, *53*, 7880–7889. [[CrossRef](#)] [[PubMed](#)]
21. Todorenko, D.A.; Slatinskaya, O.V.; Hao, J.; Seifullina, N.K.; Radenović, Č.; Matorin, D.N.; Maksimov, G.V. Photosynthetic pigments and phytochemical activity of photosynthetic apparatus of maize (*Zea mays* L.) leaves under the effect of thiamethoxam. *Agric. Biol.* **2020**, *55*, 66–76. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.