



STABLE ISOTOPE FINGERPRINTING OF RICE VARIETIES AND CULTIVATION SYSTEMS USING EA–IRMS

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Abstract

Rice (*Oryza sativa* L.) is a staple food for more than half of the global population and is available in various types, including white, red, black, brown, and basmati rice. Authentication of rice varieties and cultivation systems is increasingly important for ensuring food quality and preventing fraud. This study aimed to characterize the stable isotope composition of different rice types and to evaluate isotopic differences between organic and conventional cultivation systems using Elemental Analyzer–Isotope Ratio Mass Spectrometry (EA–IRMS). Carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope ratios were measured in seven rice samples. The results showed that $\delta^{13}\text{C}$ values ranged from -30.33‰ to -28.06‰ , confirming that all samples belong to the C_3 photosynthetic group, while $\delta^{15}\text{N}$ values ranged from 4.29‰ to 6.05‰ , reflecting variability in nitrogen sources and soil processes. Each rice type exhibited a distinct isotopic profile, indicating the potential of isotope ratios as fingerprints for varietal differentiation. However, isotopic differences between organic and conventional samples were not consistently distinguishable due to overlapping values. These findings suggest that stable isotope analysis has potential as a tool for rice authentication in the Indonesian market. Nevertheless, the limited sample size in this study indicates that the results should be considered preliminary, and further validation using larger datasets and multivariate statistical approaches is required to improve classification accuracy.

Keywords : isotope ratio, EA–IRMS, rice authentication, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$

INTRODUCTION

Rice (*Oryza sativa* L.) serves as the primary food source for more than half of the world's population, with the majority of consumption concentrated in Asia (Bandumula, 2018). In Indonesia, white rice remains the most widely consumed type; however, colored and specialty varieties such as red rice, brown rice, and black rice are also present in the domestic market (Mogoginta et al., 2024). Each type exhibits distinctive nutritional and sensory attributes (Malabadi et al., 2022). For example, black rice contains high levels of anthocyanins, pigments that impart a dark hue and possess antioxidant properties, whereas red rice contains lower levels of these compounds (Chen et al., 2022), while brown rice differs from white rice mainly by the retention of its bran layer, which is associated with lower eating quality but improved health benefits (Huang et al., 2021).

From a chemical perspective, isotopes provide another dimension for studying agricultural products. The term originates from the Greek isos (equal), referring to atoms of the same element that share identical atomic numbers but differ in mass due to variations in neutron count. Isotopes may exist in stable or radioactive forms. Stable isotopes do not emit radiation, while radioactive isotopes undergo decay accompanied by energy release. Carbon, for instance, has both stable isotopes (C-12 and C-13) and a radioactive form (C-14) (Georgiou & Danezis, 2015). The use of isotope ratios as analytical markers has gained increasing attention because isotopic composition is often species-specific and can be influenced by environmental and geographical factors (Gori et al., 2025). Such analyses have been applied in food authentication and origin tracing (Kim et al., 2013). Nevertheless, limited research has addressed isotopic variation across different rice varieties.

Isotope Ratio Mass Spectrometry (IRMS) is a key analytical technique for determining stable isotope ratios in biological and agricultural materials (Chen & Bontempo, 2025). The instrument measures the relative abundance of isotopes such as $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ by ionizing gaseous samples and separating ions according to their mass-to-charge ratios in a magnetic field (Lancaster et

al., 2025). Stable carbon isotope ratio mass spectrometry (IRMS) is an advanced analytical technique capable of providing insights into the chemical composition, biological origin, and geographical provenance of materials (Birch et al., 2021). This approach provides precise isotopic fingerprints that can reveal differences related to plant metabolism, cultivation conditions, or geographical origin (Chen & Bontempo, 2025)

Previous studies have demonstrated the application of isotope ratio mass spectrometry (IRMS) in determining the geographical origin and authenticity of various agricultural commodities. However, limited studies have systematically evaluated isotopic variation across multiple rice varieties and cultivation systems, particularly in the Indonesian market context. Therefore, this study aims to characterize the stable isotope composition of different rice types and to explore their potential for distinguishing cultivation systems. This study represents one of the few investigations of stable isotope variation across multiple rice varieties in the Indonesian market.

METHODS

Materials and Equipment

An Elemental Analyzer (EA) coupled with an Isotope Ratio Mass Spectrometer (IRMS) was used for isotopic analysis. Additional tools included a micro analytical balance, tinfoil cups, and standard laboratory equipment. Seven rice samples representing five varieties (white, red, black, brown, and basmati) were analyzed. Organic and conventional samples were identified based on commercial labeling.

Sample Preparation

Rice grains were ground using a chopper until a fine powder (minimum 100 mesh) was obtained. Approximately 300 μg of each powdered sample was weighed into a tinfoil cup using a micro analytical balance. Each sample was analyzed in duplicate. A Certified Reference Material (CRM), Caffeine Sigma Aldrich, with a known isotopic ratio, was also weighed and analyzed under identical conditions.

The tinfoil cups containing samples were tightly folded and loaded into the autosampler

of the EA-IRMS instrument. The EA was operated at a combustion temperature of 1020°C and a column temperature of 70°C. The

carrier and reference gases used were ultra-high-purity helium, set at 100 mL/min for the carrier and 70 mL/min for the reference flow.

Data Analysis

Isotope ratios were expressed in per mil (‰) relative to international standards using Equation (1):

$$\delta \text{ (‰)} = \frac{(R_{\text{Sample}} - R_{\text{standard}})}{R_{\text{standard}}} \cdot 1000$$

(1)

where R represents the isotope ratio of the sample (either test or standard).

One-way ANOVA was used to evaluate differences among samples. Due to limited sample size, further multivariate analysis was not performed but is recommended for future studies. A positive δ value ($\delta > 0$) indicates that the sample is enriched in the heavier isotope compared to the standard, while a negative δ value ($\delta < 0$) indicates depletion in the heavier isotope.

RESULTS DAN DISCUSSION

Variation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ among Rice Varieties

In this study, seven rice samples representing five rice varieties were analyzed to determine their carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope compositions. The isotopic differences among rice types are interpreted descriptively based on mean values and observed variation. The highest $\delta^{13}\text{C}$ value was found in basmati rice ($-28.06 \pm 0.039\text{‰}$), whereas the lowest was observed in black rice ($-30.33 \pm 0.007\text{‰}$). For nitrogen isotopes, the highest $\delta^{15}\text{N}$ value was observed in conventional white rice ($6.05 \pm 0.118\text{‰}$), while the lowest occurred in organic red rice ($4.29 \pm 0.042\text{‰}$).

The $\delta^{13}\text{C}$ values obtained in this study ranged from -30.33‰ to -28.06‰ (Table 1), which fall within the typical isotopic range of C_3 plants. According to Kohn (2010), C_3 plants generally exhibit $\delta^{13}\text{C}$ values between -20‰ and -37‰ , reflecting the characteristic carbon isotope discrimination associated with the Calvin photosynthetic pathway. Therefore, the isotopic signatures observed in all rice samples confirm that the analyzed varieties follow the C_3 photosynthetic mechanism.

Despite belonging to the same photosynthetic group, noticeable variation in $\delta^{13}\text{C}$ values was observed among the rice samples, indicating differences in physiological responses and growth conditions. Specifically, basmati and red conventional rice exhibited relatively less negative $\delta^{13}\text{C}$ values (-28.06‰ and -28.90‰ , respectively), suggesting lower stomatal conductance and reduced C_i/C_a ratios,

which are commonly associated with water-limited conditions and higher water use efficiency. In contrast, black and brown rice showed more negative $\delta^{13}\text{C}$ values (-30.33‰ and -30.23‰), indicating higher stomatal openness and growth under more favorable water availability. Organic rice samples (white and red organic) displayed slightly more negative $\delta^{13}\text{C}$ values compared to their conventional counterparts, suggesting relatively higher stomatal conductance and potentially lower water use efficiency.

Such variation can be attributed to differences in environmental and physiological factors, including water availability, stomatal conductance, light intensity, and nutrient status, which influence carbon isotope discrimination during photosynthesis (Rogers et al., 2022; Eggels et al., 2021). In C_3 plants, these factors regulate the ratio of intercellular to atmospheric CO_2 concentration (C_i/C_a), which directly controls the degree of isotopic fractionation (Cernusak et al., 2013). Lower stomatal conductance under water-limited conditions reduces the C_i/C_a ratio and results in less negative $\delta^{13}\text{C}$ values, whereas well-watered conditions generally lead to more negative $\delta^{13}\text{C}$ values (Saurer et al., 2004). Accordingly, the carbon isotopic composition of plants reflects variation in transpiration efficiency among C_3 species (Richards, 2006). Consequently, even rice plants grown under different microenvironmental conditions or cultivation systems may exhibit distinct $\delta^{13}\text{C}$ signatures. In addition to environmental controls, slight genetic differences among cultivars may also contribute to variability in physiological

responses, further influencing isotopic composition (Richards, 2006). This finding aligns with previous studies demonstrating that $\delta^{13}\text{C}$ can serve as an integrative indicator of plant water-use efficiency and environmental adaptation (Xiao et al., 2026).

In addition, $\delta^{15}\text{N}$ values ranged from 4.29‰ to 6.05‰ (Table 2), indicating variability in nitrogen sources and cycling processes among the rice samples. Nishida (2018) reported that $\delta^{15}\text{N}$ values in organic rice typically range from 3.1 to 8‰, which is consistent with the results of this analysis. Notably, variation in $\delta^{15}\text{N}$ values was also observed across the seven individual samples, suggesting that each sample reflects distinct nitrogen dynamics influenced by its specific growing conditions. Conventional rice samples generally exhibited slightly higher $\delta^{15}\text{N}$ values compared to organic rice, which may indicate differences in nitrogen inputs and soil nitrogen transformations. However, the variation observed among individual samples suggests that this pattern is not uniform across all varieties. Some samples within the same cultivation category displayed overlapping $\delta^{15}\text{N}$ values, highlighting the influence of site-specific factors such as fertilizer type, application method, and microbial activity in the soil (Nishida, 2018). Interestingly, this finding contrasts with several previous studies reporting that organically grown rice often exhibits higher $\delta^{15}\text{N}$ values due to the

application of organic fertilizers. The discrepancy observed in this study may therefore be attributed to differences in local agricultural practices, mixed nitrogen sources, or environmental conditions affecting nitrogen cycling processes (Guo et al., 2024). Indeed, $\delta^{15}\text{N}$ values are known to vary widely in both organic and conventional systems, making it difficult to rely on a single $\delta^{15}\text{N}$ threshold as a definitive indicator of cultivation practice. Therefore, while $\delta^{15}\text{N}$ provides valuable insights into nitrogen sources and biogeochemical cycling, its interpretation should be approached cautiously and ideally integrated with other indicators, such as $\delta^{13}\text{C}$, to improve the reliability of rice discrimination.

Furthermore, the application of isotope ratio mass spectrometry (IRMS) has been increasingly recognized as a reliable tool for food authentication and traceability studies. Isotopic fractionation processes are strongly influenced by geo-climatic factors, environmental conditions, cultivation practices, and plant physiological responses. As reported by Wadood et al. (2024), isotopic fingerprints combined with multivariate statistical analysis provide a robust approach to differentiate rice based on cultivar type and geographical origin. Their study demonstrated that $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures could effectively distinguish Pakistani basmati rice from non-basmati varieties, highlighting the potential of stable isotope analysis in verifying food authenticity.

Table 1. Measurement results of $\delta^{13}\text{C}$ values in rice samples.

Rice type	White Organic	Red Organic	White Conventional	Red Conventional	Black	Basmati	Brown
$\delta^{13}\text{C}$ (‰, VPDB)	-29.82	-29.90	-29.31	-28.85	-30.34	-28.02	-30.14
	-29.79	-29.76	-29.36	-28.95	-30.32	-28.10	-30.32
Unc.	0.011	0.068	0.027	0.047	0.007	0.039	0.089
Mean	-29.81	-29.83	-29.34	-28.90	-30.33	-28.06	-30.23

Table 2. Measurement results of $\delta^{15}\text{N}$ values in rice samples.

Rice type	White Organic	Red Organic	White Conventional	Red Conventional	Black	Basmati	Brown
$\delta^{15}\text{N}$ (‰, VPDB)	5.65	4.25	5.94	6.08	5.57	5.52	4.14
	5.68	4.34	6.17	5.95	5.44	5.44	4.58
Unc.	0.027	0.042	0.118	0.066	0.069	0.038	0.215

Mean	5.67	4.29	6.05	6.02	5.5	5.48	4.36
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Reference Standard: Caffeine Sigma Aldrich ($\delta^{13}\text{C} = -31.14 \pm 0.15\text{‰}$; $\delta^{15}\text{N} = -2.94 \pm 0.11\text{‰}$)

Measured values reflect the differences in chemical composition among rice samples. Basmati rice contains 2-acetyl-1-pyrroline, which is the source of its unique flavour and aroma (Kasote et al., 2021). Black rice and red rice contain anthocyanin, a flavonoid-group compound that serves as antioxidant. The differences are black rice contains more anthocyanin than red rice (Basith et al., 2023). Differences between chemical compounds could be one of the causes of the variations of isotopic values within each rice sample.

Although the present study did not specifically investigate the effects of geographic and environmental factors on isotope ratios, previous studies have demonstrated that such factors can significantly influence isotopic signatures in plant materials. Variations in soil composition, climate conditions, altitude, and other environmental parameters have been reported to alter the distribution of stable isotopes, potentially affecting the interpretation of isotopic data (Rogers et al., 2022; Ren and Yu, 2011). Water availability affects carbon isotopic composition. Ratio of ambient intercellular humidities reflects changes in energy budget of leaves, which influence by stomata conductance. Plants growing under water-stressed condition are expected to be enriched with ^{13}C compared to plants growing under optimal water conditions (Wang et al., 2022). Stomata tend to open wider under optimal water conditions which increases the CO_2 diffusion into the leaves. This condition increases discrimination of heavy isotopes and reduces the value of $\delta^{13}\text{C}$ into more negative (Wang et al., 2022). Nitrogen isotopic composition is affected by the source of nitrogen itself, fertilization process and nitrogen cycle. Synthetic N fertilizers created by Haber-Bosch reaction tends to have $\delta^{15}\text{N}$ value near zero due the nitrogen source for the reaction itself come from atmosphere. Natural fertilizers, like compost or organic waste shows higher $\delta^{15}\text{N}$ value due isotope fractionation during the decomposition and mineralization processes. Microbial activities like nitrification, denitrification, ammonification and ammonia volatilization increase nitrogen fractionation

even more, making the $\delta^{15}\text{N}$ value even higher (Robinson, 2001).

Overall, the results of this study demonstrate that stable isotope fingerprints, particularly $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, not only reflect plant physiological responses but also provide a powerful tool for rice characterization and authentication. While $\delta^{13}\text{C}$ primarily captures variations related to photosynthetic processes and water-use efficiency, $\delta^{15}\text{N}$ offers complementary insights into nitrogen sources and cultivation practices. Importantly, measurable differences observed among the seven rice samples indicate that each sample exhibits a distinct isotopic signature, even when some belong to the same variety group. This variation suggests that isotopic composition is influenced not only by genetic factors but also by environmental conditions and agricultural management practices specific to each sample. Therefore, the combined use of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, particularly when integrated with multivariate statistical analysis, enhances the robustness of isotopic fingerprinting in discriminating rice samples based on both varietal identity and production environment.

Differentiation of Organic and Conventional Rice

The differentiation between organic and conventional rice was further evaluated based on their $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotopic compositions. Differences in isotopic signatures are expected due to variations in cultivation practices, including water management, fertilizer application, and soil conditions (Yuan et al., 2018). These factors influence plant physiological responses and nutrient dynamics, which are ultimately reflected in isotopic fractionation (Snyder et al., 2022).

In terms of $\delta^{13}\text{C}$, organic rice samples generally exhibited slightly more negative values compared to conventional rice. This pattern suggests relatively higher stomatal conductance and differences in water-use efficiency, potentially influenced by soil fertility and management practices in organic systems (Saurer et al., 2004). However, the magnitude of these differences was relatively small, indicating that $\delta^{13}\text{C}$ alone may not

provide a strong basis for distinguishing between cultivation systems. For $\delta^{15}\text{N}$, conventional rice samples tended to show slightly higher values compared to organic rice. This observation differs from several previous studies, which reported higher $\delta^{15}\text{N}$ values in organically grown crops due to the application of organic fertilizers (Guo et al., 2024). The overlap in $\delta^{15}\text{N}$ values observed in this study suggests that nitrogen isotope composition is strongly affected by site-specific factors, such as fertilizer type, application method, and soil microbial activity (Nishida, 2018). The combined interpretation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ provides a more comprehensive understanding of the differences between organic and conventional rice. While each isotope individually shows limited discriminatory power, their integration enhances the ability to detect subtle variations associated with agricultural practices. This combined approach improves the reliability of isotopic analysis for distinguishing cultivation systems.

Overall, although isotopic differences between organic and conventional rice were observed, the presence of overlapping values indicates that stable isotopes alone may not always provide definitive discrimination. Therefore, the application of multivariate statistical analysis is recommended to improve classification accuracy. This approach allows for a more robust differentiation by integrating multiple isotopic and environmental variables.

CONCLUSION

This study demonstrated that stable isotope analysis using $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ provides valuable insights into the physiological responses and cultivation conditions of rice. The $\delta^{13}\text{C}$ values (-30.33‰ to -28.06‰) confirmed that all rice samples belong to the C_3 photosynthetic group, while the observed variation among samples reflected differences in water availability, stomatal conductance, and environmental conditions during plant growth. In contrast, $\delta^{15}\text{N}$ values (4.29‰ to 6.05‰) indicated variability in nitrogen sources and soil nitrogen cycling processes, highlighting the influence of agricultural practices and site-specific factors.

The results further showed that each of the seven rice samples exhibited a distinct isotopic signature, even among samples within

the same variety group. Although organic rice tended to display slightly more negative $\delta^{13}\text{C}$ values and conventional rice showed relatively higher $\delta^{15}\text{N}$ values, overlapping isotopic ranges limited the ability to clearly distinguish cultivation systems based on single isotope parameters. These findings indicate that isotopic composition is governed by a complex interaction of genetic, environmental, and management factors.

Overall, the combined use of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ demonstrates potential for rice characterization and authentication. However, due to the limited sample size and the presence of overlapping isotopic values, the results should be interpreted as preliminary. Future studies incorporating larger sample sets and multivariate statistical analysis are necessary to enhance the robustness and reliability of isotopic fingerprinting for distinguishing rice varieties and cultivation systems.

REFERENCES

- Bandumula, N. (2018). Rice Production in Asia: Key to Global Food Security. *Proceedings of the National Academy of Sciences India Section B - Biological Sciences*, 88(4), 1323–1328. <https://doi.org/10.1007/s40011-017-0867-7>
- Basith, A., Noer, S., & Faizah, M. (2023). VARIASI TINGKAT KANDUNGAN ANTOSIANIN PADA EMPAT VARIETAS LOKAL PADI BERAS HITAM (*Oryza sativa* L.) INDONESIA. *Jurnal Pertanian*, 14(1): 1-6. <https://doi.org/10.30997/jp.v14i1.7152>
- Birch, Q. T., Potter, P. M., Pinto, P. X., Dionysiou, D. D., & Al-Abed, S. R. (2021). Isotope ratio mass spectrometry and spectroscopic techniques for microplastics characterization. *Talanta*, 224. <https://doi.org/10.1016/j.talanta.2020.121743>
- Cernusak, L. A., Ubierna, N., Winter, K., Holtum, J. A. M., Marshall, J. D., & Farquhar, G. D. (2013). Environmental and physiological determinants of carbon isotope discrimination in terrestrial plants. In *New Phytologist* (Vol. 200, Number 4, pp. 950–965). <https://doi.org/10.1111/nph.12423>

- Chen, L., & Bontempo, L. (2025). Application of isotope ratio mass spectrometry (IRMS) in the geographical determination of selected herbs: A review. *TrAC Trends in Analytical Chemistry*, *183*, 118107. <https://doi.org/https://doi.org/10.1016/j.trac.2024.118107>
- Chen, X., Yang, Y., Yang, X., Zhu, G., Lu, X., Jia, F., Diao, B., Yu, S., Ali, A., Zhang, H., Xu, P., Liao, Y., Sun, C., Zhou, H., Liu, Y., Wang, Y., Zhu, J., Xiang, Q., & Wu, X. (2022). Investigation of flavonoid components and their associated antioxidant capacity in different pigmented rice varieties. *Food Research International*, *161*, 111726. <https://doi.org/https://doi.org/10.1016/j.foodres.2022.111726>
- Eggels, S., Blankenagel, S., Schön, C. C., & Avramova, V. (2021). The carbon isotopic signature of C4 crops and its applicability in breeding for climate resilience. In *Theoretical and Applied Genetics* (Vol. 134, Number 6, pp. 1663–1675). Springer Science and Business Media Deutschland GmbH. <https://doi.org/10.1007/s00122-020-03761-3>
- Georgiou, C. A., & Danezis, G. P. (2015). Chapter 3 - Elemental and Isotopic Mass Spectrometry. In Y. Picó (Ed.), *Comprehensive Analytical Chemistry* (Vol. 68, pp. 131–243). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-444-63340-8.00003-0>
- Gori, Y., Deklerck, V., & Camin, F. (2025). Stable isotope ratio analysis to determine the geographical origin of timber: A review. *TrAC Trends in Analytical Chemistry*, *193*, 118448. <https://doi.org/https://doi.org/10.1016/j.trac.2025.118448>
- Guo, Z., Li, C., Li, X., Shao, S., Rogers, K. M., Li, Q., Li, D., Guo, H., Huang, T., & Yuan, Y. (2024). Fertilizer Effects on the Nitrogen Isotope Composition of Soil and Different Leaf Locations of Potted *Camellia sinensis* over a Growing Season. *Plants*, *13*(12). <https://doi.org/10.3390/plants13121628>
- Huang, M., Li, X., Hu, L., Xiao, Z., Chen, J., & Cao, F. (2021). Comparing texture and digestion properties between white and brown rice of indica cultivars preferred by Chinese consumers. *Scientific Reports*, *11*(1). <https://doi.org/10.1038/s41598-021-98681-7>
- Kasote, D., Singh, V. K., Bollinedi, H., Singh, A. K., Sreenivasulu, N., & Regina, A. (2021). Profiling of 2-acetyl-1-pyrroline and other volatile compounds in raw and cooked rice of traditional and improved varieties of india. *Foods*, *10*(8). <https://doi.org/10.3390/foods10081917>
- Kim, K. S., Kim, J. S., Hwang, I. M., Jeong, I. S., Khan, N., Lee, S. I., Jeon, D. B., Song, Y. H., & Kim, K. S. (2013). Application of stable isotope ratio analysis for origin authentication of pork. *Korean Journal for Food Science of Animal Resources*, *33*(1), 39–44. <https://doi.org/10.5851/kosfa.2013.33.1.39>
- Kohn, M. J. (2010). Carbon isotope compositions of terrestrial C3 plants as indicators of (paleo)ecology and (paleo)climate. *Ecology*, *107*. <https://doi.org/10.1073/pnas.1004933107/-/DCSupplemental>
- Lancaster, S. T., Irrgeher, J., Dallmayr, R., Conrad, E., Hörhold, M., Bohleber, P., Behrens, M., Camin, F., Žagar, K., Vreča, P., & Prohaska, T. (2025). $\delta(18O/16O)$ Determinations in Water Using Inductively Coupled Plasma–Tandem Mass Spectrometry. *Analytical Chemistry*, *97*(38), 20788–20797. <https://doi.org/10.1021/acs.analchem.5c02607>
- Malabadi, R. B., Kolkar, K. P., & Chalannavar, R. K. (2022). *White, and Brown Rice–Nutritional value and Health benefits; Arsenic Toxicity in Rice plants. International Journal of Innovation Scientific Research and Review*, *04*(07), 3065–3082.
- Mogoginta, J. G., Murai, T., & Annor, G. A. (2024). Starch Characteristics and Amylopectin Unit and Internal Chain Profiles of Indonesian Rice (*Oryza sativa*). *Foods*, *13*(15). <https://doi.org/10.3390/foods13152422>
- Nishida, M. (2018). *Natural $15N$ Abundance Can Aid the Discrimination of Organic and Conventional Rice. Japan International Research Center for*

- Agricultural Sciences*, 53(3), 173-180.
<https://doi.org/10.6090/jarq.52.173>
- REN, S.J., & YU, G.R. (2011). Carbon isotope composition ($\delta^{13}\text{C}$) of C3 plants and water use efficiency in China. *Chinese Journal of Plant Ecology*, 35(2), 119-124. doi: 10.3724/SP.J.1258.2011.00119
- Richards, R. A. (2006). Physiological traits used in the breeding of new cultivars for water-scarce environments. *Agricultural Water Management*, 80(1-3), 197-211. <https://doi.org/10.1016/j.agwat.2005.07.013>
- Robinson, D. (2001). $\delta^{15}\text{N}$ as an integrator of the nitrogen cycle. *Trends in Ecology & Evolution*, 16(3), 153-162. [https://doi.org/https://doi.org/10.1016/S0169-5347\(00\)02098-X](https://doi.org/https://doi.org/10.1016/S0169-5347(00)02098-X)
- Rogers, K. M., Martin, A. P., Pradel, G., Yuan, Y., Zhang, Y., & Turnbull, R. E. (2022). Elemental and isotopic compositions of New Zealand regional soils identifies human and climate-induced effects. *Applied Geochemistry*, 143, 105356. <https://doi.org/https://doi.org/10.1016/j.apgeochem.2022.105356>
- Saurer, M., Siegwolf, R. T. W., & Schweingruber, F. H. (2004). Carbon isotope discrimination indicates improving water-use efficiency of trees in northern Eurasia over the last 100 years. *Global Change Biology*, 10(12), 2109-2120. <https://doi.org/10.1111/j.1365-2486.2004.00869.x>
- Snyder, K. A., Robinson, S. A., Schmidt, S., & Hultine, K. R. (2022). Stable isotope approaches and opportunities for improving plant conservation. In *Conservation Physiology* (Vol. 10, Number 1). Oxford University Press. <https://doi.org/10.1093/conphys/coac056>
- Wadood, S. A., Chunlin, L., Nie, J., Rogers, K. M., Mei, H., Zhang, Y., Shah, I. U., Qamar, A., & Yuan, Y. (2024). Stable isotopic fingerprinting of authentic basmati rice from Pakistan. *Food Control*, 157. <https://doi.org/10.1016/j.foodcont.2023.110166>
- Wang, Z., Liu, J., Wang, Y., Agathokleous, E., Hamoud, Y. A., Qiu, R., Hong, C., Tian, M., Shaghaleh, H., & Guo, X. (2022). Relationships between stable isotope natural abundances ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) and water use efficiency in rice under alternate wetting and drying irrigation in soils with high clay contents. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.1077152>
- Xiao, Y., Liu, J., Li, Y., Wang, Z., Xin, P., Zhang, J., Zhang, M., Lu, N., Wang, J., & Ma, W. (2026). Leaf morphology- $\delta^{13}\text{C}$ synergy in drought response and G×E interactions in *Toona sinensis*. *Trees, Forests and People*, 24. <https://doi.org/10.1016/j.tfp.2026.101189>
- Yuan, Y., Zhang, W., Zhang, Y., Liu, Z., Shao, S., Zhou, L., & Rogers, K. M. (2018). Differentiating Organically Farmed Rice from Conventional and Green Rice Harvested from an Experimental Field Trial Using Stable Isotopes and Multi-Element Chemometrics. *Journal of Agricultural and Food Chemistry*, 66(11), 2607-2615. <https://doi.org/10.1021/acs.jafc.7b05422>