Agricultural optimization through radioactive tracer technology: applications, challenges, and future directions

Abstract

Radioactive tracer technology serves as a transformative method for investigating physiological and biochemical processes within fruit crops. By employing isotopes, this technique enables precise tracing, imaging, and molecular-level diagnostics. This review highlights its significant applications, including optimizing nutrient dynamics, analyzing water transport mechanisms, enhancing photosynthetic efficiency, and managing pest-related challenges. The paper also delves into the logistical, safety, and economic hurdles associated with the technology. Furthermore, it emphasizes the transformative role of machine learning and advanced imaging techniques in expanding the potential and efficacy of radioactive tracer applications in agricultural research.

Keywords: Isotopes, radioactivity, detection, agricultural applications

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Introduction

Radioisotopes are unstable isotopes that achieve stability by emitting radiation in the process of radioactive decay. This phenomenon, discovered by Henri Becquerel in 1896 during his study on uranium, was later expanded upon by Marie Curie. In 1943, George de Hevesy introduced the tracer technique, marking a pivotal moment in the application of radioisotopes for tracing processes within biological systems (Marykate et al., 2012). Today, radioactive tracer technology is extensively employed in agricultural research to understand growth dynamics, optimize productivity, and enhance crop management strategies (Nakanishi et al., 2023).

The selection of isotopes for tracing applications is determined by various factors, including their half-life, decay modes, and the types of radiation they emit. Short-lived isotopes, like Technetium-99m, are particularly valuable for diagnostic purposes, providing rapid results without significant radiation exposure to the subject. A quick decay provides an ideal for medical imaging and real-time tracking in living systems (Sugita et al., 2017). In contrast, isotopes with longer half-lives, such as Carbon-14, are well-suited for studies that require extended observation periods, such as in archaeology and paleontology, where dating ancient materials or tracking long-term processes is essential (Babin et al., 2022).

This paper specifically explores the role of radioactive isotopes in agricultural research, focusing on their application in fruit crops. By tracing the movement and uptake of nutrients and water in plants, isotopes can help improve crop management, optimize fertilizer use, and enhance pest control strategies. The paper also highlights the challenges of using isotopes in agriculture, such as ensuring safety, managing environmental impact, and addressing regulatory concerns. Furthermore, it discusses emerging opportunities for integrating isotopic techniques with modern agricultural technologies, like precision farming and sustainable agriculture, to optimize crop production and support agricultural innovation.

Sources of radioactive

Natural and Artificial radioistopes

Radioactive emissions are a widespread occurrence in our environment and can originate from both natural and artificial (man-made) sources (Cerezo et al., 2023). Natural radiation primarily comes from extraterrestrial cosmic rays and the radionuclides found in the Earth's crust and bodies of water. These natural sources of radiation are part of the background radiation we encounter daily. Internal sources of radiation, on the other hand, arise from radioactive materials that enter our bodies through intake or medical procedures, such as injections. Examples of naturally occurring radioisotopes include uranium-238 (^{238}U92), thorium-232 ($^{232}Th_{90}$), potassium-40 ($^{40}K_{19}$), rubidium-87 ($^{87}Rb_{37}$), and carbon-14 ($^{14}C_{6}$) (Kovler et al., 2017).

Artificial radiation, in contrast, results from human activities, such as nuclear explosions, nuclear reactor operations, medical treatments, agricultural practices, scientific research, and industrial applications. These man-made sources of radiation can involve radionuclides used in a variety of fields. Some examples of radioisotopes associated with artificial radiation include cobalt-60 ($^{60}Co_{27}$), plutonium-238 ($^{238}Pu_{94}$), and americium-241 ($^{241}Am_{95}$) (Jadiyappa, 2018). Radioisotopes release various types of radiation, which can manifest either as particles or electromagnetic waves. The five main types of radiation emissions from radioisotopes are alpha (α) particles, beta (β) particles, gamma (γ) rays, X-rays, and neutrons (Abdelmotelb et al., 2023).

Radioactive Decay and Disintegration Rate

Radioactive decay refers to the spontaneous emission of radiation, often leading to the transformation of one nucleus into another, especially when emitting alpha or beta particles. The rate of radioactive disintegration is directly proportional to the number of nuclei present in the product (Sugihara, 2015). The decay rate is essential for predicting the behaviour of radioactive materials over time and for various scientific and industrial applications (Dragović, 2022). The importance of radioisotopes is mentioned in Table 1.

Table 1. Radioisotopes importance in plant (Jadiyappa et al., 2018)

S.No.	Radioisotopes	Half- life	Emission	Uses
1.	^{55}Fe	2.6 years	Beta	Soil erosion, foliar nutrition, soil availability
2.	^{64}Cu	12.8 hours	Gamma	Soil and plant movement
3.	^{58}Co	71 days	Gamma	Plant enzyme studies, vitamin metabolism
4.	^{51}Cr	27.8 days	Gamma	Plant and Soil movement
5.	^{35}S	87 days	Beta	Soil availability, S cycle, Uptake
6.	^{45}Ca	165 days	Beta	Ion uptake, soil exchangeable Ca
7.	^{32}P	14.3 days	Beta	Fertilizers, root distribution, rock phosphates
8.	^{18}O	0.204 %	Stable	Photosynthesis, Respiration, Hydrology
9.	^{3}H	12.3 years	Beta	Water movement, Metabolism
10.	^{75}Se	120 days	Gamma	Plant movement
11.	^{36}Cl	3.08×10^{5}	Beta	Salt tolerant, solute movement in

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		years		soils
12.	^{99}Mo	66.7 hours	Gamma	Plant movement
13.	^{65}Zn	245 days	Gamma	Plant and Soil movement
14.	^{54}Mn	314 days	Gamma	Soil movement
15.	^{14}C	5720 years	Beta	Photosynthesis, organic matter, C balance
16.	^{15}N	0.366 %	Stable	Fertilizers, BNF, N balance
17.	^{41}K	11.29 %	Stable	Fertilizer, K balance
18.	^{28}Mg	21.3 hours	Beta	Movement in plants, environmental pollution
19.	^{22}Na	2.6 years	Gamma	Cell permeability and salt tolerant

Radioactivity: Detection and measurement

Accurate detection and measurement techniques are crucial for effectively quantifying and mapping the distribution of radiotracers within a given system. In agricultural applications, for instance, the concentration of radiotracers in plant tissues is often used to assess the uptake and movement of nutrients or other substances. Various types of radiation detectors are employed, each tailored for specific detection mechanisms based on the nature of the radiation and the system under study (Nakashini, 2018).

The most common detection methods include scintillation detectors, liquid scintillation detectors (LSDs), crystal scintillation detectors, Geiger-Müller counters, dosimeters, autoradiography, spectrometers, radiometers, and gas ionization detectors (Fathy et al., 2024). Each of these technologies operates based on different principles, from measuring the ionization of particles to detecting light emitted by scintillators when radiation interacts with them.

In real-time detection of radioisotopes, radioisotope imaging systems are widely used. These systems employ a scintillator, which absorbs the radiation emitted from a plant after the application of radioisotopes. The absorbed radiation is then converted into light, which is captured by a fiber optic plate (FOS). A highly sensitive charge-coupled device (CCD) camera is used to record this light image, providing precise real-time visualization of the radioisotope's distribution within the plant system (Nakanishi, 2018 and Xiong et al., 2024). This technology allows researchers to closely monitor how radiotracers move through plant tissues, offering valuable insights into nutrient uptake and other physiological processes.

Applications of Radioactive Tracer Technology

A classical use of tracer technique is in radiocarbon dating for tracing the Quantitative information generation, Identification of the source of soil water and its availability to plants, estimation of their contribution, dynamics of photosynthates/assimilates to understand crop nutrition, measurement of biological nitrogen fixation, extent of soil erosion and crop protection and pest control (Figure.1) (Reiffarth et al., 2016).

Nutrient Uptake and Translocation

Radioactive tracers such as ^{3}H, ^{14}C, ^{32}P, ^{35}S and ^{86}Rb are very useful in nutrient dynamics in soil. Radioisotopes like 32P and 42K are instrumental in analyzing nutrient dynamics in soil-plant systems. Their application has enhanced fertilizer use efficiency and provided insights into nutrient absorption mechanisms (Klement, 2019). In banana plants (*Musa spp.*),

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P-32 has been used to understand phosphorus uptake under varying soil conditions, contributing to optimized fertilization practices (Nyombi, 2020).

Photosynthesis and Carbon Assimilation

The basic mechanisms of nutrient metabolism and translocation in plants are investigated using Carbon-14 (Babin et al., 2022). Carbon-14 is widely used to trace carbon pathways, offering critical insights into photosynthetic efficiency and carbon allocation. Studies on grapevines (*Vitis vinifera*), demonstrated the drought impacts carbon assimilation and redistribution, aiding in the development of stress-resistant cultivars (Pagay et al., 2022).

Water Movement

A radioactive tracer is very useful in estimating the movement of soil water or the age of water in an aquifer. Tritium-labeled water (3H) facilitates the study of water uptake, transport, and utilization in crops. These insights are crucial for understanding water stress responses and improving irrigation strategies (Kulikova et al., 2016). Tritium tracing in citrus plants has revealed critical information on hydraulic failure thresholds during prolonged drought (HuiBai and QiLan, 2008).

Soil-Plant Interactions

Radioactive tracers facilitate the study of nutrient interactions in the rhizosphere, root architecture, and root-soil interactions. Root exudate studies in mango (*Mangifera indica*) plants have used labelled isotopes to understand nutrient mobilization (Muñoz-Redondo et al., 2021). Radioisotopes such as ^{137}Cs, ^{210}Pb and ^{7}Be are useful in assessing soil erosion losses and sedimentation rates. The pattern of root activity distribution obtained using radioactive ^{32}P compared well with the actual (Babu et al., 2014).

Pest and Disease Management

Radioactive tracers are pivotal in evaluating pest impacts on nutrient flow and crop physiology. Techniques such as the Sterile Insect Technique (SIT), which uses gamma irradiation to sterilize pests, have proven effective in integrated pest management systems. As a result, it enhances the crop production and preservation of natural resources (Gómez-Simuta et al, 2021). The impact of pests and pathogens on nutrient flow in fruit crops can be studied using radioactive tracers. This has led to more targeted pest and disease management strategies. Leaf spot disease in bananas has been linked to disrupted nutrient flow, as demonstrated using P-32 tracers. Radioisotopes including ^{14}C, ^{32}P, ^{35}S, ^{35}C1, ^{74}As, ^{75}As, ^{208}Hg and ^{3}H being used for labeling pesticide molecules (Shen et al., 2021).

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Challenges and Safety Concerns

Radioactive Decay and Stability

The variable half-lives of isotopes necessitate precise selection for specific applications. Short-lived isotopes pose logistical challenges in handling and transportation (Sugita et al., 2017).

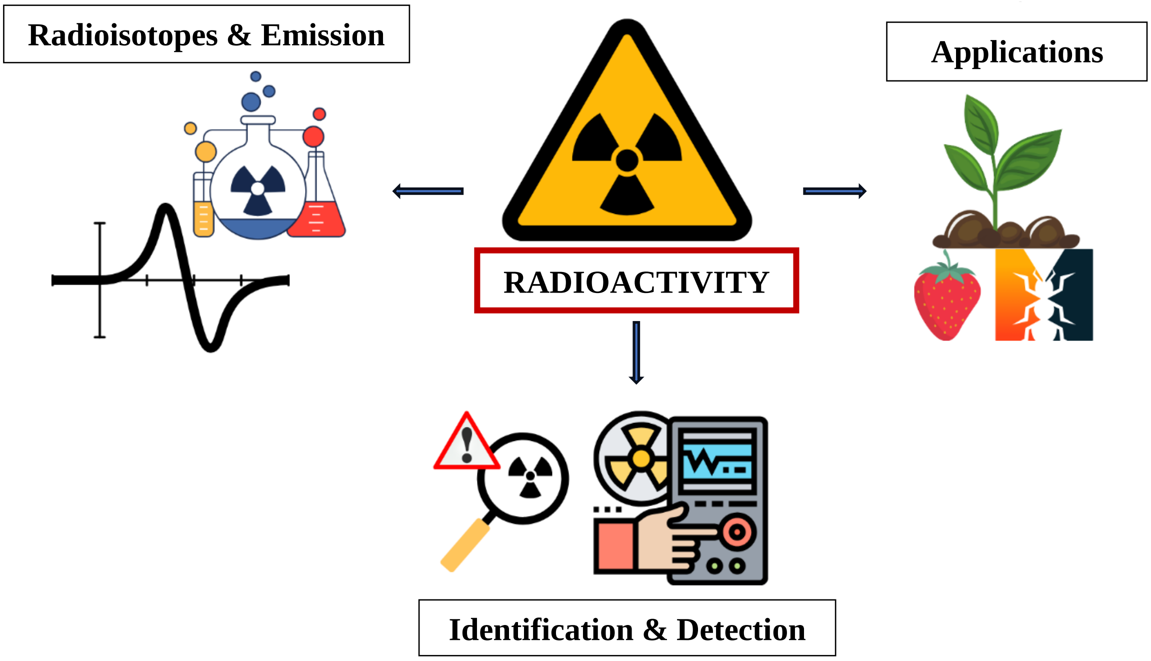
Safety Protocols

The use of radioactive materials requires strict guidelines for the handling, storage, and disposal of radioactive materials are essential to prevent environmental contamination and ensure researcher safety (Kovler et al., 2017).

Cost and Accessibility

High costs and limited accessibility of radiotracer equipment hinder widespread application, especially in resource-constrained settings (Cerezo et al. 2023).

Figure 1. Radioactive technology and application



Future Prospects

Integration with Machine Learning

Combining radiotracer data with machine learning algorithms can enhance predictive modelling, enabling better decision-making in crop management and breeding programs (Galib et al., 2020).

Advancements in Imaging Techniques

The development of high-resolution imaging methods, such as autoradiography and positron emission tomography (PET), can provide detailed spatial and temporal insights into tracer movement within plants (Kurita et al., 2020).

Isotopic Labeling in Breeding Programs

The use of radioactive tracers to identify traits linked to nutrient efficiency and stress tolerance can support sustainable agricultural practices, paving the way for more resilient crop varieties (Regner et al., 2018).

Conclusion

Radioactive tracer technology has transformed our understanding of crop physiology and biochemistry. While challenges such as safety concerns and high costs persist, advancements in technology and interdisciplinary approaches promise to expand its

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applications. By integrating tracers with modern tools, researchers can unlock new opportunities to enhance crop productivity and sustainability.

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