REVIEW ARTICLE

Nuclear Technique Applications Vis-A-Vis Soil Fertility and Plant Nutrition: An Overview

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Abstract

Nuclear techniques in agriculture encircle the exploitation of isotopic and radiation techniques to contend with diseases and pests, upsurge production of crops, water, and land resource protection, safeguard food safety in hand with authenticity and elevate the production of livestock. Nuclear techniques intend to ease trials regarding food security, safety, and sustainable agriculture development. Nuclear techniques in the circle of agriculture have paid significantly to the growth of isotopic techniques to assess soil deterioration apart from the creation of effective soil and land conservation approaches. These interventions encompass fallout radionuclides encircling ^{137}Cs, ^{210}Pb and ^{7}Be and compound specific stable Isotopes (CSSI) techniques. The sensitive estimates of total N_2 fixation across the growth cycle of leguminous crops reside in the isotopic method application with the employment of a stable ^{15}N isotope, usually at enrichment as well as natural abundance levels. The utilization of Oxygen-18 and Hydrogen-2 aids to study the utilization of plant water, the quantification of agricultural transpiration, and the development of tactics to boost crop productivity, minimize unproductive losses of water, and check water as well as land degradation. For the comprehension of biological courses and mechanisms of ecosystem functioning, nuclear-based approaches are supportive tools, not a replacement for conventional techniques. As a result, a thorough assessment of the demand for employing a nuclear/isotopic technique, as well as selection of an apt isotopic technique, is required, taking into account the objective of research, facilities and expertise accessible, and affiliated risks in view of safe conduct and disposal of menacing constituents in addition to the financial considerations.

Keywords: Compound Specific Stable Isotopes (CSSI), Evapotranspiration, Land degradation, Nuclear and isotopic techniques

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Introduction

Food security is a major challenge for the growing global population as there are more mouths to feed worldwide than ever before. By 2050, the current escalating population of the world is anticipated to surpass nine billion (Islam *et al.*, 2019). The call for heightened food production would have to be doubled to meet this requisition, the demand being most prominent in developing countries (FAO, 2017). By 2050, the amount of agricultural land could be reduced by 95%, owing to the application of current technologies, which have the potential to reduce soil erosion with farming land degradation rates by up to 5-7 million ha annually (Avagyan, 2021). So, there is a long-lasting call for enhanced food security along with food safety and sustainability.

Agriculture contributes significantly to anthropogenic global warming, and decreasing agricultural emissions, particularly nitrous oxide and methane, can help mitigate climate change (Lynch *et al.,* 2021). Therefore, agricultural production systems stipulate a combined attitude in the improvisation of crop productivity to ensure food safety in hand with security and at the same time aid in the restoration of soil quality with enhanced resilience contrary to degradation and risks affiliated with imprints of changing climate. Nuclear technology has proven to be useful in the search for sustainable methods of producing more food while limiting environmental effects. Nuclear technology is defined as the technology that manipulates the changes in the atomic nuclei of specific elements and their translation into energy. It is used in the production of nuclear energy. Agriculture nuclear applications rely on the employment of isotopic as well as radiation approaches to contest pests and illnesses, enhance crop productivity, safeguard terrestrial and aquatic ecosystems, verify the safety and authenticity of the food produced, and increase livestock production (FAO, 2017).

Soil fertility, irrigation, and crop production are significant aspects of crop production because they encompass the

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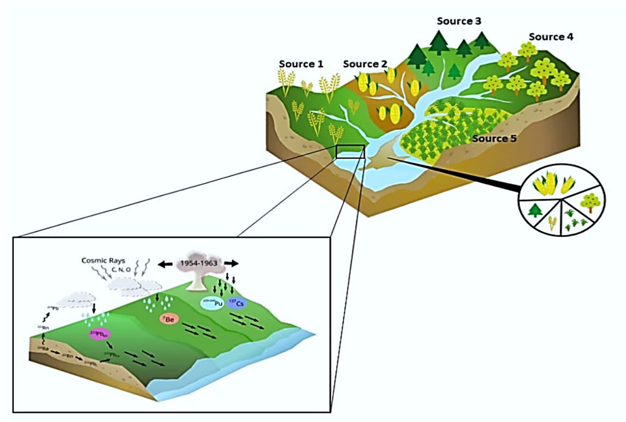

Fig. 1: Compound Specific Stable Isotopes (CSSI) and Fallout Radionuclides (FRNs for investigation of soil erosion, transport and sedimentation processes (Mabit *et al.* 2018)

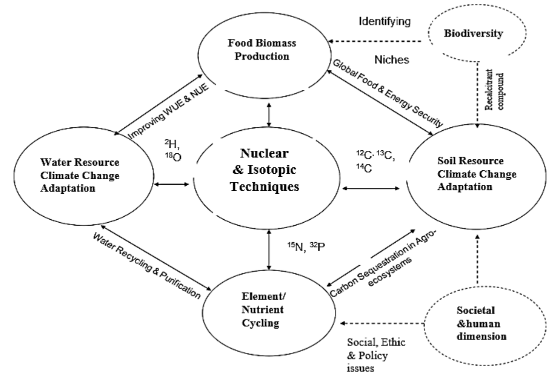

Fig. 2: Nuclear and isotopic techniques' role in addressing global concerns of sequestering carbon for advancement in food security and mitigation of climate change (Nguyen, 2014).

important combinations of healthy, productive soils and an appropriate water supply required to produce high-quality crop production. Nuclear techniques are being developed to improve the effectiveness of fertilizers, better understand their environmental consequences, and not discover fresh applications for their restricted usage. Nuclear and/or isotopic techniques are being employed as tracers to acquire a healthier comprehension of courses prevailing in soil water-plant nexus in hand with their intricate relationships. These techniques are also being utilized to develop agro-ecosystem-specific soil-water management solutions.

As a result of the introduction of the integrated nutrient management module (which includes both fertilizer manufacturing and natural nutrient sources encompass animal and green manures, rock phosphates, biological nitrogen fixation etc. in conjunction with crop residue recycling, the employment of nitrogen-15 (^{15}N), phosphorus-32 (^{32}P), and sulphur-35 (^{35}S) isotopes as tracers has opened the door to the development of precision agriculture (Nguyen *et al.,* 2010). The employment of stable isotopes (oxygen-18 (^{18}O), carbon-13 (^{13}C), nitrogen-15 (^{15}N), deuterium (^{2}H) and sulphur-34 (^{34}S) to examine the nutrient and water dynamics existing in soil-plant structures has advanced significantly in the last decade (Gautam and Lee, 2016). In addition, the employment of stable and radioactive isotopes offers an imperative part in hydrological investigations and provides vital information such as aquifer–aquifer interconnection, groundwater age and sources of groundwater pollution (Sankoh *et al*., 2021) However, before the adoption of any nuclear isotopic technique, it is imperative to consider the pros and cons affiliated with these techniques (Table 1).

Applications Of Nuclear Techniques

Assessment of soil erosion

Land degradation and soil erosion comprise the common attributes of irreparable loss of soil fertility, decreased soil production, an increase in pollutants, and the siltation of bodies of water, among other things. The classic methods of soil erosion measurement and modelling are supplemented by more precise methods, encircling the exploitation of fallout radionuclides, which are becoming increasingly popular. Predominantly, four radionuclides (FRNs) are employed as tracers of soil erosion, encircling anthropogenic radionuclides viz., caesium-137 (^{137}Cs) possessing medium span as well as isotopes of plutonium ($^{239+240}$Pu) exhibiting long shelf life, whose sources include testing of nuclear weapons in the atmosphere in addition to the accidents from the nuclear power plant (NPP), as well as natural radionuclides viz., geogenic lead-210 (Pb^{210} and Beryllium (^{7}Be) Several studies (Alewell *et al.,* 2017; IAEA, 2014; Mabit *et al.,* 2014) have examined the effects of radiation on the environment. The underlying hypothesis for exploiting radiotracers in assessing soil erosion along with sedimentation is comparable in nature. FRNs are intensely adherent to colloidal complex of soil, such as clay and organic residues, once they have been deposited on the surface of the soil. For the mobility of these particles in the ecosystem, mechanical courses like soil erosion are entrusted with this responsibility. FRNs method execution is contingent on the establishment of FRN contents both at a reference site and in a study area, as described above. By comparing the FRN inventories of the areas under investigation to those of the reference site, it is possible to determine whether they are erosional or depositional (Fig. 1). Sites with altitudes lower than the reference site value represent eroded soils, whereas sites with levels in excess of the reference site value represent soil deposition (IAEA, 2014; Mabit *et al.,* 2008; Mabit *et al.,* 2018). Validation of plutonium isotopes ($^{239+240}$Pu) has been carried out with regard to advanced radio-isotopic approaches to estimate the rate of soil erosion in different upland agro-environments of Switzerland (Meusburger *et al.,* 2018), as well as in South Korea (Yoon *et al.,* 2021), as well as in Japan (Kim *et al.,* 2018).

Identification of hotspots of land degradation

The acquisition of information regarding sediment sources has been made affordable by studying the quantity of the ^{13}C stable isotope as well as the different ^{13}C signatures in C_3 as well as C_4 plants. Compound Specific Stable Isotopes (CSSI) are stable isotopes that are specific to a particular compound (Laceby *et al.,* 2015; Schindler Wildhaber *et al.,* 2012). In this technique,

Table 1: Some advantages (A) and disadvantages (D) of two ^{15}N isotope techniques for measuring BNF in agricultural systems (Zaman *et al.*, 2018)

Criteria	*^{15}N isotope dilution technique*	*^{15}N natural abundance technique*
Requirement of reference plants	D	D
Cost with ^{15}N fertilizer	D	A
Cost with ^{15}N analysis	D	D
Requirement of high-skilled technicians	D	D
Requirement of high-precision spectrometers	A	D
Need of considering isotope fractionation	A	D
Field variability of soil ^{15}N	A	D
Application in perennial systems	A	A
Application in experiments with soils presenting plant available N with low $\delta^{15}N$ (<4‰)	A	D
Time integrated measurement of %Ndfa	A	A
Measurement of amount of N derived from BNF per unit area	A	A

Table 2: Pros and cons of Nuclear technique applications

S. No.	*Advantages*	*Disadvantages*
1.	Low operating costs	Initial investment is quite hefty
2.	Global climate compatibility	People exposed to it possess health issues
3.	Zero Carbon emissions	Risk of nuclear accidents
4.	High energy density	Non-renewable energy source
5.	Promising energy future	High yield of radioactive wastes

the absorption of organic biomarkers by soil colloidal complex tags the soil and are reallocated as a result of soil movement are used to tag and reallocate the soil. The biomarkers have a distinct spectral signature that varies depending on the plant species, making them particularly well suited for distinguishing between soil contributions derived from various land uses and other sources (Reiffarth *et al.,* 2016; Upadhayay *et al.,* 2017). CSSI approaches assist in the identification of regions that are producing significant sediment loadings, hence exacerbating the water pollution problem (Gibbs, 2014; Heng *et al.,* 2014). Because of this, the integration of CSSI, geochemistry, and FRNs is critical in the identification of hotspots of land degradation, assisting policymakers and land managers in the identification of appropriate measures of soil conservation, and the formulation of proficient strategies for regulation of land and water resource base sustainability in the context of a specific agro-ecosystem (International Atomic Energy Agency, 2008).

Carbon sequestration and nutrient/water cycling

A primary mechanistic investigation is necessary for the stabilization of carbon in the soil, as well as for a sound comprehension of processes and drivers that guide the dynamics of soil organic carbon (SOC), in order to better understand the stabilization of carbon in the soil. A sophisticated quantification of carbon, water, and nutrient pools as well as their changes in relation to a given agroecosystem is essential for this to be accomplished (Nguyen, 2014). It is possible to obtain exclusive information on such pools and fluxes by measuring fluctuations in the natural abundance of stable isotopes (^{2}H, ^{13}C, ^{15}N, ^{18}O, and ^{34}S) in different soil constituents such as ground and surface water, biomass, atmospheric gas and soil organic matter (Fig. 2). This information could be used to manage the soil organic carbon sequestration in agricultural lands. Recent isotopic interventions, such as CSSI, and breakthroughs in the instrumentation of analytical chemistry, as well as the gathering of computational data, have been made recently for the assessment of isotope ratios in soil and plant samples, as well as water and gas samples (Crosson, 2008). As of right now, these methodologies are being used to investigate the carbon conversions and turnover in a particular ecosystem (Glaser, 2005). A powerful technique in microbial ecological research, stable isotope probing (SIP) aims to identify the active intrinsic microbial colonies in soil that have serve as ^{13}C or ^{15}N labelled substrates, depending on the inclusion of ^{13}C or ^{15}N into various cellular biomarkers encompassing nucleic acids such as DNA or RNA. The conjunctive employment of stable isotope practices and biomarkers increases the likelihood of uncovering the part of biodiversity in soil cycling of carbon, as well as the ability to gain a more nuanced understanding of the interaction that exists between vegetation and soil in carbon modelling (Staddon, 2004 Amelung *et al*., 2008)

Assessment of legume BNF using ^{15}N isotope techniques

Employing stable ^{15}N isotopes with natural abundance and at enrichment levels, isotopic methods have proven to be the most responsive methods of determining total N_2 fixation during the growing period of leguminous crops. As a result of these procedures, it is possible to distinguish between air nitrogen and other nitrogen sources present in the environment. For the evaluation of nitrogen input by N_2-fixing plants through biological nitrogen-fixation, three different parameters are considered: the amount of nitrogen present in the evaluated plant part, the output of the N_2-fixing plants in terms of dry matter in hand with the proportion of nitrogen in the nitrogen-fixing plant that has been acquired from the atmosphere (per cent Ndfa) (Zaman *et al.,* 2018). The ^{15}N isotope dilution technique and the ^{15}N natural abundance approach comprise the instrumental isotopic techniques devised to accomplish the concerned objective (Chalk and Craswell, 2018). The assessment of below-ground nitrogen occurring in roots and substrate (in the case of rhizodeposition) is required for the determination of total nitrogen fixed or nitrogen balance in the soil. Various isotopic techniques, such as ^{15}N isotope dilution, $^{15}N_2$ labelling, split root ^{15}N labelling, and a leaf or stem ^{15}N feeding, were used in these investigations (IAEA, 2001). The investigation of the numerous possible above- and belowground pathways for N transfer between nearby legume and non-legume plants has been greatly aided by the use of the stable isotope ^{15}N (Peoples *et al*., 2015) (Table 2). The stem ^{15}N labelling approach developed by McNeill (1999) has proven to be an effective method of labelling the roots of leguminous plants using 2 mL of 0.075M urea solution (containing approximately 20% 15N atom surplus)

Root activity studies using isotope techniques

The activity of roots can be traced with the employment of stable isotopes of water ($\delta^{18}O$ and δ^2H). By comparing the isotopic compositions of the source water and xylem at the same time, these isotopes can successfully determine the source of transpired water (Barbeta and Penuelas, 2017). A radioactive substance encircling ^{32}P or ^{86}Rb is inserted into the stem of the plant, and the root distribution design is calculated by considering soil-root samples placed at present locations, followed by the measurement of their radioactivity. A phosphate solution labelled with ^{32}P is inserted into the soil at different sites, and the radioactivity of plant samples is measured. This information is used to determine the pattern of root activity at the various locations in each of the experiments. The application of fertiliser in the region of the maximum root zone and when the root system is at its most active is predicted to increase the uptake of fertiliser nutrients by the crop. So that sound fertiliser practices for tree crop plantations can be developed, obtaining information on the root activity distribution pattern in different seasons is a prerequisite for developing such practices. The employment of such techniques exhibits the potential to characterize trends prevailing amid intraspecific root architecture and edaphic-dependent resource availability (Isaac and Anglaaere, 2013).

Conclusion

Nuclear and isotopic techniques are pioneering methods for land as well as water management that promote long-term sustainability. The application of nuclear and isotopic technique offer their role to study fertilizer use efficiency and sustainability of soil fertility, and soil quality and would, therefore, aid in the development of water and nutrient efficient crops varieties, assessment of farm water and irrigation management techniques that increase WUE by crops, soil erosion rates, soil profile and soil formation rates, recharge capacity of spring in addition to the promotion of integrated natural resource management within the agricultural catchment. Isotopes of light elements (C, H, N, O, and S) furnish a route to trace the origin and track the fates of discrete metabolites, nutrients as well as chemical pollutants during the course of their movement through soils, plants, food webs, soil waters and the atmosphere. When compared to conventional non-nuclear procedures, they possess the relative advantages of high specificity, accuracy, and sensitivity. Owing to these advantages, they are able to provide quantitative data, which allows them to provide straight responses to the queries addressed while sparing both times as well as effort. Nevertheless, in order to yield benefits of the nuclear/isotopic techniques selected, certain prerequisites must be met, including the accessibility of experienced and skilled human assets as well as the provision of ample contributory analytical equipment. It is not possible to apply these strategies in isolation, however, their integration with others in regional or national research opportunities in order to make the most of their potential in view of attaining effective consequences and providing people-centred remunerations may appear advantageous. When everything is said and done, the ultimate result will be enhanced efficiency in proper management of soil and water resources, improved financial perks, and sustenance of the agro-environment under fluctuating imprints of climate change.

Author's Contribution

AMS and TIS designed the concept. SN and IMK reviewed the Introduction section. SAB, AMA, ARM, MHC, YHM and GM – reviewed and edited the final version of the manuscript.

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