IANCAS Bulletin

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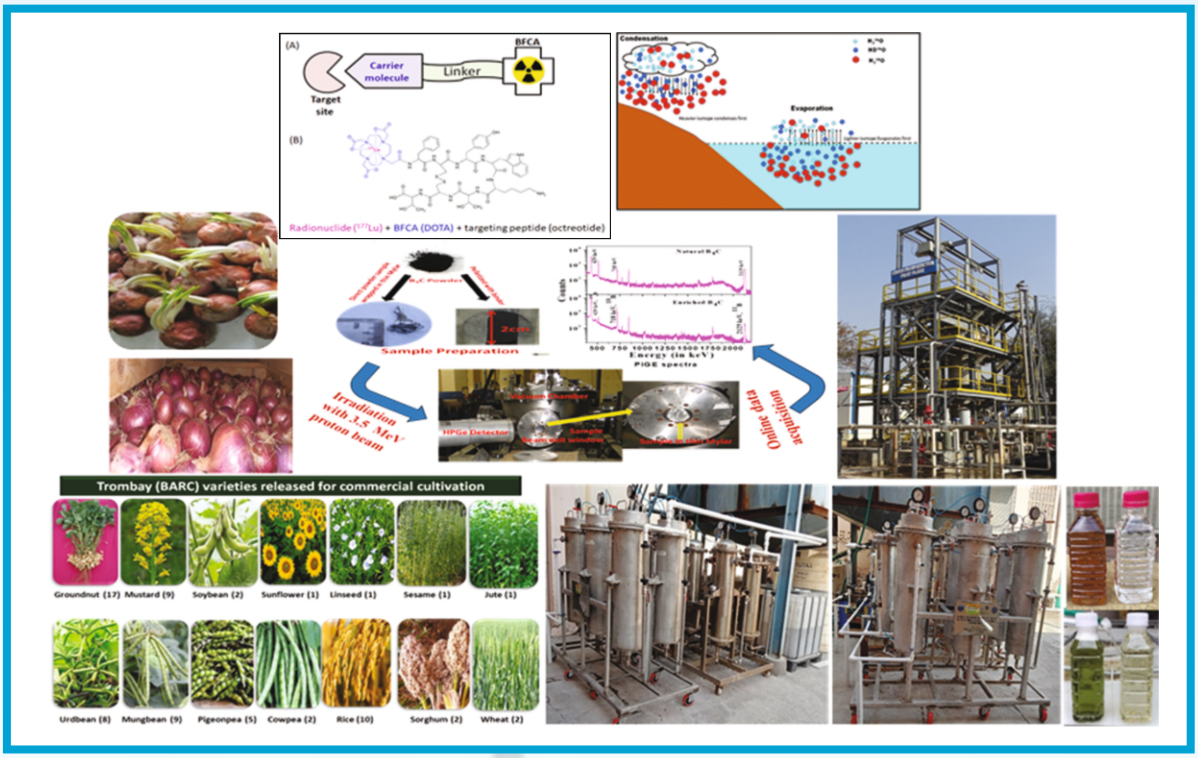
Societal and Industrial Applications of Nuclear Technologies



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IANCAS Bulletin, Volume- XX, No. 3, March 2025

IANCAS Bulletin

Societal and Industrial Applications of Nuclear Technologies

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A Publication of
INDIAN ASSOCIATION OF NUCLEAR CHEMISTS AND ALLIED SCIENTISTS (IANCAS)
(Reg. No. MAH/232/1984/GBBSD)
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(Reg. No. MAH/232/1984/GBBSD)

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(Term: 1st April 2024 – 31st March 2027)

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IANCAS acknowledges the funds provide by the BRNS for the publication of this bulletin

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FOCUS

Dr. Y.K. Bhardwaj
Associate Director, RC&IG

The Department of Atomic Energy (DAE) has been serving its motto, “Atoms in the Service of the Nation”, by delivering the benefits of nuclear science and technology to National Security, Energy Security, Food Security, Water Security and Health Security. Initially nuclear technology was more into clean energy (power) but over period of time non-power applications of nuclear technology have out-done its energy applications.

In healthcare, the use of radioisotopes for imaging in PET and SPECT has revolutionized disease detection, enabling early diagnosis of cancers and other medical disorders. Treatments like radiotherapy, using cobalt-60 and iodine-131, offer targeted destruction of malignant cells, improving patient outcomes and quality of life. A notable advancement in cancer therapy, Boron Neutron Capture Therapy (BNCT), is gaining renewed attention.

In agriculture, radiation-induced mutation breeding has led to robust crop varieties with enhanced yields and adaptability, crucial for food security. Food safety and preservation have greatly benefited from radiation technology, where gamma irradiation ensures pathogen-free produce and extends shelf life, reducing foodborne illnesses and waste.

Likewise, isotope hydrology plays a pivotal role in water resource management, offering critical data on groundwater movement and recharge. Industrially, radiotracers have become indispensable tools in process optimization, leak detection, and environmental monitoring, all while ensuring efficiency and ecological responsibility.

In materials science, radiation has unlocked new possibilities, yielding advanced materials for aerospace, medicine and smart packaging. Radiation technology enables precise modification of polymers through grafting, crosslinking, degradation and nanomaterial synthesis. This has led to advanced materials such as functional adsorbents, catalytic systems, sensors, antimicrobial coatings, and radiation-resistant polymers, highlighting its broad impact across sectors.

In analytical science the field continues to innovate with neutron and proton-based analytical techniques, enhancing non-destructive testing and environmental sample analysis.

Industrial radiology has evolved with digital imaging and tomography, offering greater accuracy and speed. Similarly, thermal neutron imaging provides non-invasive methods for studying structural integrity and environmental impacts.

As the application of isotopes and radiation technology further evolve it underscores the importance of continued research, responsible innovation, and collaborative efforts to harness nuclear science for the greater good.

I compliment the Editor, Dr. R. Acharya; Guest Editor Dr. Virendra Kumar and authors for bringing out this bulletin on “**Societal & Industrial Applications of Nuclear Technologies**” which will provide valuable inputs to aspiring and budding researchers & personnel working in the domain of non-power applications of nuclear technology.

(Dr. Y. K. Bhardwaj)

President's Message

Application of radio-isotopes, for myriad societal issues, has been one of the major spinoffs of the nuclear industry. Major part of these radioisotopes is being employed in nuclear medicine for both diagnostic as well as therapeutic applications and this has been covered in some recent volumes of IANCAS bulletin. Apart for those, there are applications of radioisotopes in industry, archeological dating, environmental tracing, biological science, isotope hydrology, etc. The industrial applications of radiotracers include leak detection, fluid flow monitoring, determining mixing efficiency in chemical reactors and gauge engine wear and corrosion of process equipment, etc. Radioisotopes are also used in biological sciences viz. molecular biology, metabolic studies, protein studies, etc., while they can also be used to understand the movement of pollutants in the environment. Isotope hydrology applications of radioisotopes such as ^{3}H and ^{14}C give important information on the ground water flow and age. Other beneficial information includes recharge source, recharge rate, aquifer interactions, etc. by analysing the natural isotopes of water.

All of us are aware of the versatility of X-rays and gamma rays in diagnostic applications. These radiations also find many societal applications out of which the major ones include sterilization of medical equipment's, food irradiation, mutation breeding, radiography for non-destructive testing, etc. Industrial radiography exploits the ability of gamma rays to penetrate materials to inspect the integrity of poured concrete and welds on fluid vessels, pipelines, critical structural elements, etc.

Radiation technology has emerged as a game-changer in polymer research, offering innovative methods to modify and enhance the properties of polymers for diverse applications. By exposing polymers to controlled doses of radiation, researchers can induce cross-linking, grafting, or degradation, thereby tailoring their mechanical, thermal, and chemical characteristics. This has led to the development of advanced materials such as radiation-resistant polymers for aerospace, biocompatible hydrogels for medical devices, and smart packaging materials that respond to environmental stimuli. Additionally, radiation is used to sterilize medical equipment, ensuring safety and efficacy.

The current issue of the IANCAS bulletin gives a broad overview and insights into the societal and industrial applications of radioisotopes and radiations. I would like to extend my sincere appreciation to the guest editor of this important issue, Dr. Virendra Kumar, Head, RTDD, and Dr. Sunil Goswami, IRAD, for their efforts in compiling and editing. The contributors of this bulletin have done a praiseworthy job in preparing excellent articles to make this a very precious volume. Finally, I commend the hard work rendered by all concerned in the making of this Bulletin.

(Dr. P.K. Mohapatra)

President, IANCAS

From the Secretary's Desk

Indian Association of Nuclear Chemists and Allied Scientist (IANCAS) was founded in 1981 with an objective of popularizing Nuclear and Radiochemistry, Applications of Radioisotopes, and Nuclear Techniques among the scientific community in India. For this purpose, IANCAS is continuously organizing seminars, workshops and publishing periodic thematic Bulletins focused on fundamentals of Nuclear and Radiochemistry, and applications of radioisotopes in education, research, agriculture, medicine and industry. With active participations of the life-members, IANCAS has become one of the popular associations for popularizing the subject of Nuclear and Radiochemistry across the country.

IANCAS through its various outreach programs motivate the young researchers and scientists to apply Nuclear and Radiochemistry based methods in their respective research field. In addition, IANCAS life-members through IANCAS activities motivate students to pursue a career in the field of Nuclear Science. For the promotion of Nuclear Science among the researchers, IANCAS has instituted three awards; (i) Dr. M. V. Ramaniah Memorial Award (ii) Dr. Tarun Dutta Memorial Award, and (iii) Prof. H. J. Arnikar best thesis Award. All these three Awards are conferred annually. Dr. M. V. Ramaniah Memorial Award is conferred to an outstanding scientist for the significant contributions in the field of Nuclear and Radiochemistry during his/her lifetime. Dr. Tarun Dutta Memorial Award is given to a scientist (below 45 years age) having significant contributions in the field of Nuclear and Radiochemistry including the applications of radioisotopes. Prof. H. J. Arnikar best thesis Award is given for the PhD thesis focused on Nuclear and Radiochemistry, and application of radioisotopes etc. IANCAS publishes thematic Bulletins on the topics directly related to the Nuclear Science and Technology with the financial support from BRNS, DAE. These Bulletins are distributed free to all IANCAS life-members, and are made freely available at IANCAS website (www.iancas.org.in) for download. The association's popular book on "Fundamentals of Nuclear and Radiochemistry" is widely sought amongst the academia, researchers and students from DAE and Universities. In the series of IANCAS Bulletins, the present Bulletin titled "**Societal & Industrial Applications of Nuclear Technologies"** aims at giving details of applications of nuclear technologies for societal and industrial applications.

Information about the workshops, Awards and various activities of IANCAS are available on the website (www.iancas.org.in). All the publications of IANCAS including Bulletins and books are also available at the website.

(Dr. Sandeep Kumar Sharma)

Secretary, IANCAS

From Editor's Desk

Most important applications of Radioisotopes and Radiation Technology are focused towards societal benefits in the sectors of healthcare/nuclear medicine, agriculture, food, industry, and water resource management. For implementation of these non-power applications of radioisotopes & radiation, in urban as well as rural areas, many human resources / trained man-power are very essential and, in this direction, BARC & DAE units are engaged for maximum societal benefits and quality life. Innovative R&D works as well as unique applications in areas of interest to our department as well as to our Country are being sincerely carried out by experts of Nuclear Scientists and Technologist in general from Science and Engineering disciplines at BARC as well as at various DAE units. No doubt, radioisotopes and radiation technology have profoundly impacted society, offering solutions spanning from healthcare, agriculture & industry to environment. The Present Thematic Bulletin by IANCAS on "**Societal & Industrial Applications of Nuclear Technologies"** aims at providing various applications of radioisotopes and radiation technology in eight chapters including TT&CD activities for implementation of BARC-DAE Technologies as given here: **Chapter 1.** Radiotracer Application in Industry, **Chapter 2:** Application of isotope hydrological techniques in water resources, **Chapter 3:** Radiation processed functional materials for Environmental remediation: A brief insight, Chapter **4: Food Irradiation Technology**: Potential Role in Agro-Economical Sustainability, Chapter **5: Nuclear Agriculture** – Developments and Accomplishments, **Chapter 6:** Potential of Nuclear Analytical Techniques for Industrial and Societal Applications, **Chapter 7:** Radiopharmaceuticals Applications and Recent Advancements in Radiopharmaceuticals, **Chapter 8:** Boron Neutron Capture therapy: current status and historical perspectives, **Chapter 9:** Industrial Radiology: Conventional to computational methods for Non-Destructive Evaluation, **Chapter 10:**Societal and Industrial Applications of Thermal Neutron Imaging and **Chapter 11**: BARC-DAE Technologies for Industry & Society.

On behalf of IANCAS, I thank all authors/contributors of the chapters for sharing their R&D as well as applied works and without their contributions the Bulletin would have been incomplete. I thank both Guest Editors Dr Virendra Kumar, Head, Radiation Technology Development Division (RTDD), BARC and Dr Sunil Goswami, SO (F), IRAD, BARC for sparing their valuable time and shaping this Bulletin in this form, without their whole-hearted support, this important bulletin would not have been possible. Sincere thanks to President & all Executive Committee members of IANCAS for the continued support & time to time suggestions to bring out such types of thematic bulletins. We sincerely thank Director, BARC and Chairman, AEC & Secretary, DAE for their support towards IANCAS activities and IANCAS Publications.

On-Behalf of IANCAS, sincere thanks and acknowledgement to **Board of Research in Nuclear Sciences (BRNS), DAE** for financial support towards publications of such thematic bulletins in the line of mandate of DAE for societal applications**. T**his bulletin, like earlier ones, will also be available online in the IANCAS Web-site: www.iancas.org.in.

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Guest Editorial

The advent of radioisotopes and radiation technology has revolutionized numerous fields, offering innovative solutions to some of the most pressing challenges in healthcare, agriculture, food preservation, and environmental management. This preface introduces the remarkable applications of radioisotopes and radiation technologies, highlighting their transformative impact cross diverse sectors and their potential in shaping a sustainable future of our coming generations. This bulletin is an ensemble of 11 articles covering various aspects of nuclear and radiation technologies for societal and industrial applications.

Radiation technology has emerged as a game-changer in materials research, offering innovative methods to modify and enhance the mechanical, thermal, and chemical characteristics of these materials for diverse applications. Fundamentally, the interaction of ionising radiation with matter yields chemically reactive species, which are subsequently used for modifications of polymer via grafting, crosslinking, degradation processes and radiolytic synthesis of nanomaterials. This has led to the development of advanced materials such as radiation grafted functional adsorbents and catalytic systems for pollution remediation, sensors, antimicrobial and antifouling surfaces, radiation-resistant polymers, hygienization of sewage sludge, etc.

Radiotracer applications, on the other hand, have proven invaluable in industrial processes, environmental monitoring, and scientific research. By using trace amounts of radioisotopes, engineers and scientists can study complex systems, detect leaks in pipelines, and monitor pollution levels, ensuring efficiency and environmental protection

Isotope hydrology, another critical application, leverages radioisotopes to study water resources, trace groundwater movement, and assess aquifer recharge rates. This information is vital for managing water supplies, especially in regions facing scarcity, and for addressing challenges related to climate change and population growth.

Agriculture has also benefited immensely from radioisotope applications. Through radiation-induced mutation breeding, scientists have developed crop varieties with improved yield, disease resistance, and adaptability to harsh environmental conditions. Radioisotopes are further used to study soil fertility, optimize fertilizer use, and trace nutrient uptake in plants, contributing to sustainable farming practices and food security.

In the realm of food preservation, radiation processing has emerged as a safe and effective method to extend shelf life and eliminate harmful pathogens. By exposing food to controlled doses of gamma radiation, spoilage is minimized, and the risk of foodborne illnesses is significantly reduced, ensuring safer consumption and reducing food waste.

In healthcare, radioisotopes have become indispensable tools for diagnosis, treatment, and research. Techniques such as positron emission tomography (PET) and single-photon emission computed tomography (SPECT) rely on radioisotopes to provide detailed images of internal organs, enabling early detection of diseases like cancer and cardiovascular disorders. Additionally, radiotherapy using isotopes such as cobalt-60 and iodine-131 has saved countless lives by targeting and destroying malignant cells with precision

This compilation seeks to explore the multifaceted applications of radioisotopes and radiation technologies, emphasizing their role in advancing technology, improving quality of life, and addressing global challenges. As we delve into these topics, I believe that readers will gain a deeper appreciation for the profound impact of radioisotopes and radiation technology, and recognize their potential to drive innovation and progress for better and sustainable livelihood to our future generations.

I take this opportunity to thank all the authors who have contributed articles for this special IANCAS bulletin. It was indeed an enjoyable experience compiling this bulletin. I thank IANCAS for entrusting me with this opportunity.

(Dr. Virendra Kumar)

Guest Editorial

Nuclear technologies continue to revolutionize multiple sectors by offering innovative and sustainable solutions. In industry, radioisotopes and advanced imaging techniques enhance precision in manufacturing and infrastructure maintenance, ensuring safety and efficiency. Environmental applications, such as isotope hydrology and radiation-based waste treatment, address critical challenges like water scarcity and pollution, promoting ecological balance. In agriculture, nuclear techniques boost food production and safety through irradiation and crop improvement, supporting global food security. The medical field benefits immensely from radiopharmaceuticals and cutting-edge therapies like BNCT, which improve diagnostic accuracy and cancer treatment outcomes. Additionally, BARC-DAE exemplify how nuclear research can be translated into practical, societal benefits, from affordable healthcare tools to sustainable agricultural innovations. As these technologies evolve, interdisciplinary collaboration and public awareness will be key to maximizing their potential, paving the way for a future where nuclear science drives progress across industries while safeguarding human health and the environment.

I express my sincere thanks to IANCAS for giving me this opportunity to compile this bulletin. Heartfelt gratitude to all the authors for sharing their experiences and contributing the chapter for this thematic bulletin.

(Dr. Sunil Goswami)

Chapter 1: Application of Radioisotopes in Industry

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Abstract: *Radiotracers are extensively used for troubleshooting, measurement of hydrodynamic parameters, characterization of mixing and flow visualization in industrial process systems because of their specific advantages over conventional tracers. The commonly carried out applications include leak detection in buried pipelines and heat exchanger systems, blockage location in buried pipelines, mixing and blending studies, wear rate monitoring, flow rate measurements, residence time distribution studies in process vessels, sediment transport investigation in ports, effluent dispersion studies, ground water velocity measurement and flow tracing in oil fields. Radioactive particle tracking technique is also used for flow visualization in laboratory or pilot-scale industrial systems and validation of the computational fluid dynamic codes. Isotope Application Division, Bhabha Atomic Research Centre, Mumbai alone has carried out hundreds of large-scale radiotracer investigations during last four decades to benefit the Indian industry. Some of the commonly carried out applications are briefly discussed with recent case studies.*

1. Introduction

Applications of radioisotopes and radiation technology in industry, medicine and agriculture form an important part of India's programme of using nuclear technology for societal benefits. Radioisotope production in India started on a modest scale soon after 1 MW APSARA reactor at Trombay, Mumbai became critical in 1956. Subsequently the scope of activities expanded with the commissioning of 40 MW CIRUS reactor in 1960, the setting up of modern radioisotope processing laboratories in late sixties and the production of cobalt-60 in power reactors in megacurie quantities in late seventies. As a result of these developments, India became self-sufficient in radioisotope production. The radioisotope production capacity of India received a major boost in 1985 with the commissioning of high flux 100 MW DHRUVA reactor, which provided opportunity to extend the range of radioisotopes available in the country, both in quantity as well in specific activity. The CIRUS reactor was decommissioned in year 2010 after 50 years of successful operation and 1 MW APSARA reactor was upgraded to 2 MW and renamed as APSARA-U in 2018. Today there are two research reactors i.e. DHRUVA and APSARA-U operating at Bhabha Atomic Research Centre (BARC), Trombay, Mumbai and used for production of more than 100 different radioisotopes. The produced radioisotopes are used in industry, healthcare and agriculture across the country. Board of Radiation and Isotope Technology (BRIT), Department of Atomic Energy (DAE) supplies radioisotopes and radiation equipment and BARC, Mumbai carries out research and development activities; and also offers professional service to meet the country's demand in various fields of radioisotope applications.

The application of radioisotopes in industry are classified into two categories i.e. radiotracer applications and sealed source applications. The principle of the radiotracer technique is shown in

Fig.1. In radiotracer techniques, the radioactive material in a suitable physio-chemical form similar to that of the process material is injected into the system at the inlet and its passage is monitored along the system at strategically selected locations using radiation detectors. The presence of tracer or tracer concentration obtained as a function of time at detection location(s) is plotted and information about occurrence of malfunctions, if any and hydrodynamic behaviour of the process equipment are drawn. The use of radiotracer for industrial applications is preferred over conventional tracers because of their several advantages such as high detection sensitivity, online detection, availability of wide range of compatible radiotracers and ability to be used in harsh environment. The commonly used radiotracers in industry are gamma-emitting radiotracers and are given in Table 1 [1, 2, 3].

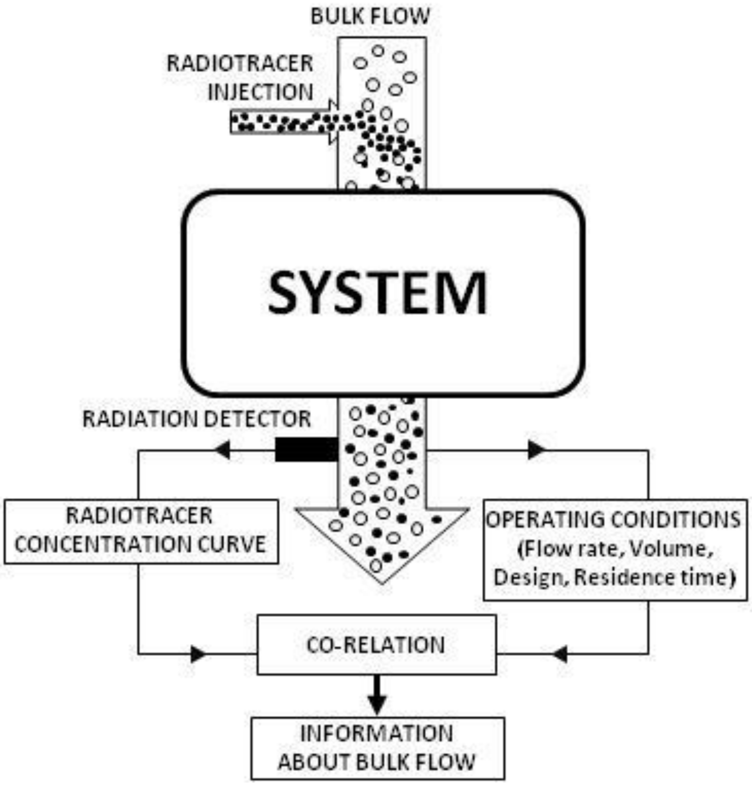

Figure 1. General principle of tracer technique [3]

In sealed source applications, a radiation source is encapsulated in a metal capsule and it never directly come in contact, with either process material or equipment. The penetrating radiation from the radiation source capsule are directed at the desired location in the equipment under investigation or material of interest and the intensity of transmitted or scattered radiation intensity is measured and analyse to draw information about content of the system or physical properties of the material. The applications of sealed source techniques are further categorized in five different categories i.e. radiometry (scanning), radiography, tomography, nucleonic control systems and radiation processing [1, 2]. The scope of the present article is limited to radiotracer applications and the sealed source applications are discussed in other chapters in this document. The commonly carried out radiotracer applications in industry by Isotope and Radiation Application Division (IRAD), BARC, Mumbai are discussed below.

2. Radiotracer Applications

2.1. Leak detection in buried pipelines and heat exchangers

Any undesirable interconnection between isolated parts of a system or between two sub-systems is called a leak. A leak is suspected in a system if there is any abnormality in the behaviour of the system such as loss of pressure, contamination of product and loss of process efficiency. Occurrence of leak in industrial systems such as buried pipelines, heat exchangers and condenser is a common problem. After suspecting a leak(s) in a system, it is essential to confirm and identify the leak(s) at the earliest to avoid deterioration of product quality, loss of process efficiency, minimize risk in safety and avoid environmental hazards. In most of the cases, conventional tracer techniques are often not feasible for leak detection in industrial systems. Therefore, the radiotracer techniques are commonly used for leak detection and location in industrial system due to their above-mentioned advantages over conventional tracers. The leak detection is probably the most widespread application of radiotracers for industrial troubleshooting with highest benefit to cost ratio [4].

Table 1. Most commonly used radiotracers in industry

Isotope	Half-life	Radiation and energy (MeV)	Chemical form	Tracing of phase
Tritium (H-3)	12.6 y	β: 0.018 (100%)	Tritiated water	Aqueous
Sodium-24	15 h	γ: 1.37 (100%) 2.75 (100%)	Sodium carbonate	Aqueous
Bromine-82	36 h	γ: 0.55 (70%) 1.32 (27%)	Ammonium bromide, p-dibromobenzene, dibrobiphenyl, methyl bromide	Aqueous Organic Organic Gas
Lanthanum-140	40 h	γ : 1.16 (95%) 0.92 (10%) 0.82(27%) 2.54 (4%)	Lanthanumchloride	Solid (Absorbed)
Gold-198	2.7 d	γ: 0.41 (99%)	Chloroauric acid	Solid(Absorbed)
Iodine-131	8.04 d	γ : 0.36 (80%) 0.64 (9%)	Potassium or sodium iodideIodobenzene	Aqueous Organic
Molybdenum-99	67 h	γ : 0.18 (4.5%) 0.74 (10%) 0.78 (4%)	Sodium molybate	Aqueous
Technetium-99m	6 h	γ : 0.14 (90%)	Sodium technetate	Aqueous
Scandium-46	84 d	γ : 0. 89 (100%) 1.84 (100%)	Scandium oxide	Solid (Particles)
Krypton-85	10.6 y	γ : 0.51 (0.7%)	Krypton	Gas
Krypton-79	35 h	γ : 0.51 (15%)	Krypton	Gas
Argon-41	110 min	γ : 1.29 (99%)	Argon	Gas

The methodology for leak detection in buried pipelines depends upon the situation and varies case to case basis. Location of actual leak position is a little more complicated as the monitoring procedure needs to be designed to suit each specific application. Three methods i.e. radiotracer-detector pig method, velocity drop method, tracer patch migration method are commonly used of leak detection in buried pipelines [1, 2]. A case study using tracer patch migration method is discussed below in details.

A 74 km long buried pipeline was laid for carrying ethylene gas from a gas cracking plant to the premises by a petro-chemical industry. During the pre-commissioning trials, a Rapid loss of pressure was observed in an 11 km long section of the pipeline indicating occurrence of the leak(s). Therefore, it was required to locate the leak(s) before commissioning the pipeline. The layout of the 11 km long section of the pipeline, location of tracer injection and monitoring locations are shown in Fig. 2b. Radiotracer technique based on migration of a tracer patch was applied [5]. Two radiotracer tests were carried out using bromine-82 as methyl bromide gas as a radiotracer. In first test, the radiotracer gas (activity: 0.7 GBq) was instantaneously injected into the pipeline at the factory end and its passage was monitored using NaI(Tl) scintillation detectors mounted at trenches located at an interval of about 1 km (Fig. 2b). It was observed that the radiotracer gas failed to move beyond trench No. 9 located at a distance of about 10 km from the premises of the industry. This indicated occurrence of a leak between the trench No. 8 and No. 9. Therefore, the length of the pipeline suspected to be leaking was reduced to 1.8 km from 11 km. The soil surface above the leaky section (1.8 km) was monitored using portable radiation detectors and a high intensity of gamma radiations was detected at a distance of 0.5 km from trench No. 8. The soil cover (~1.5 m) at the location was excavated and exact location of the leak was visually confirmed. A hole of 15 mm size was found on the pipeline. After replacing the leaking section of the pipeline, the pressure test was repeated in the 11 km long section of the pipeline. It was observed that the pressure was still dropping but at a reduced rate indicating occurrence of another smaller leak in the section. Another radiotracer test was conducted by injecting the radiotracer gas (1.9 GBq) at the other end (SV-6 location) of the pipeline. A leak of 8 mm size was located between trench No. 5 and trench No. 6 at a distance of about 4 km from factory end. The hydrostatic pressure tests carried out after remedial measures showed that the pipeline could hold the required pressure, indicating occurrence of no further leak. The pipeline could be subsequently soon commissioned for required operation.

In case of heat exchanger or condenser, the two process fluids flow counter-currently through the two independent parts or sub-system exchanging the heat. The leakage of the process fluid between the two parts will occur if there is a significant pressure difference between the two parts. The methodology of leak detection in heat exchangers in industry using radiotracer technique is illustrated in the following example. The product produced in a refinery in India was found to be contaminated with sulfur. Leakage in the heat exchanger system in the plant was suspected to be the main reason for this contamination. The heat exchanger system consisted of six shell-tube type heat exchangers connected in series. The photograph of the system is shown in Fig. 3a. The feed and the effluent flowed counter-currently through the shell and tube side, respectively. The shell side was at a higher pressure than the tube side. So in order to confirm the suspicion and identify the leaking exchanger(s), a radiotracer test was conducted by injecting a suitable radiotracer (bromine-82 as dibromobiphenyl) into the shell side and monitoring the presence of leaked radiotracer at tube sides. The schematic diagram of the experimental setup is shown in Fig. 3b. Care was taken to inject adequate quantity of the radiotracer so that the lowest suspected leak rate will result in the detection of the radiotracer. Based on the monitored radiotracer concentration curves, two heat exchangers (E-1E and E-1F) were confirmed to be leaking. The leak rate in the two exchangers was estimated to be about 0.2-0.3 % of the feed rate. Based on the results of the radiotracer test, decision was taken by the plant engineer to shut down the plant for remedial measures. The leaks in the two heat exchangers were visually confirmed during the shutdown. The timely confirmation and identification of the leaking heat exchangers reduced the shutdown time of the plant by about 15 days leading to significant revenue savings to the refinery [6, 7].

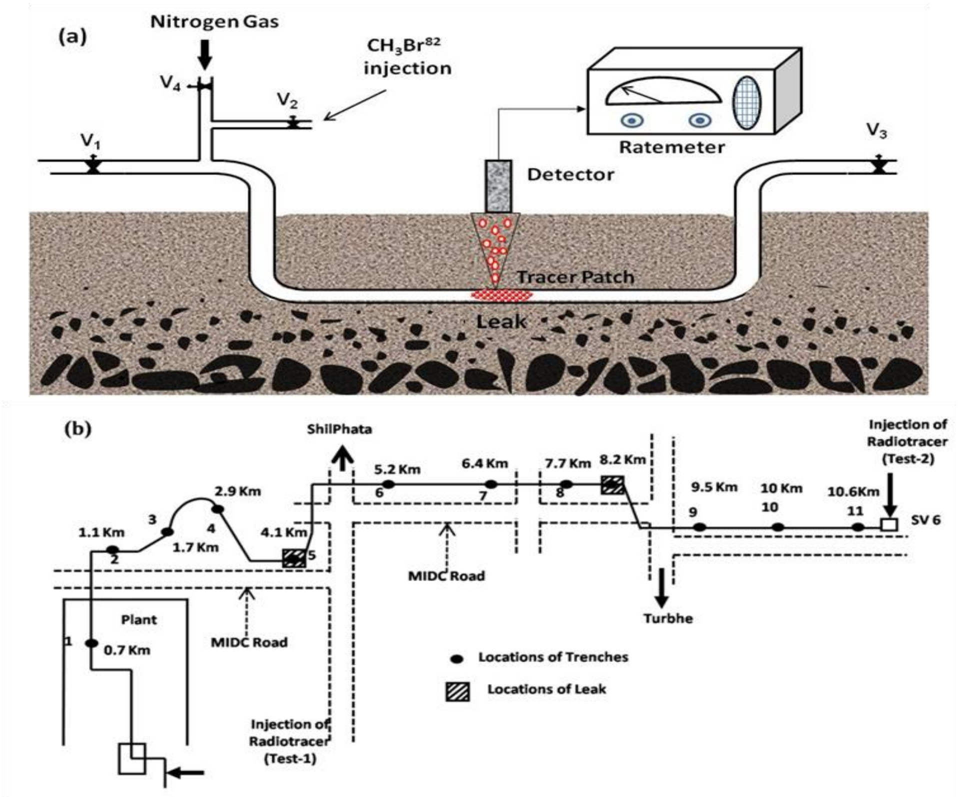

Figure 2. (a) Principle and application of leak detection in buried pipeline (b) leak detection in an ethylene gas pipeline using radiotracer patch method [5]

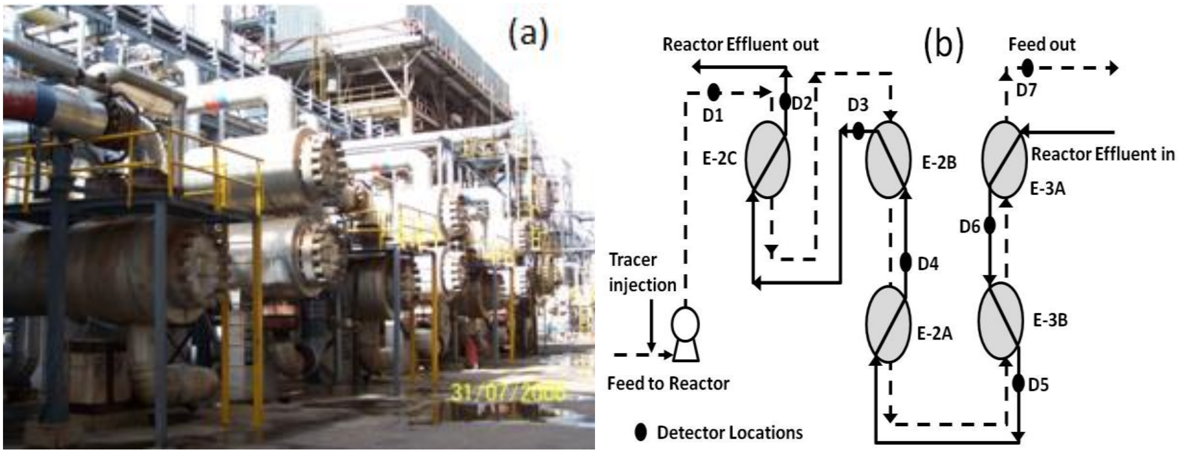

Figure 3. (a) A typical heat exchanger system in a refinery and (b) Schematic diagram for conducting radiotracer investigation [8]

2.3. Flow rate measurement

Accurate measurement of flow rates of fluids in pipelines and industrial systems is an essential requirement for assessing the efficiency of the process and to obtain product of good quality. Different conventional methods are available for measurement of flow rates in pipelines, canals and rivers. However, in some specific industrial situations, it is not possible to measure the flow rates of the process material accurately using conventional methods. In such situations, radiotracer techniques are very suitable for flow rate measurements because of their above-mentioned advantages. Usually, two different radiotracer techniques known as pulse velocity method and dilution method are often used for flow-rate measurements in industry [1, 2]. An application of the radiotracer dilution method is illustrated in the following case study.

A power company in India commissioned a 1040 MW coal based thermal power plant at the coast of the Bay of Bengal at Vishakhapatnam, Andhra Pradesh, India to cater the increasing power demand in the state [8]. The plant consists of two different units, which drew sea water for cooling and condensation of exhaust steam. The sea water is pumped and supplied to the condensers in each unit through two independent pipelines (3.6-meter diameter) using four different Vertical Turbine (VT) pumps. Ultrasound based flow meters were installed on both pipelines for measurement of flow rates and quantification of total quantity of water pumped. Based on the total quantity of water drawn for cooling/condensation, an appropriate tax amount was to be paid to the government by the company owning the plant for utilizing the water resources. The installed flow meters with digital display showed readings of flow rate with large fluctuations. Therefore, it was required to measure the accurate flow rates of water in the pipelines, to validate the pumping efficiencies of the VT pumps against the efficiencies estimated theoretically from the characteristics curves of the pumps. The theoretically estimated value of efficiency of each pump claimed by the designer and manufacturer was 15 m^3/s. In addition to this, the accurate measurement of flow rates was also required to optimize the power consumption in the plant. Since the conventional methods could not be applied, radiotracer dilution method was used for the flow rate measurements. The schematic diagram of the flow rate measurements is shown in Fig. 4. A radiotracer solution of known initial concentration (C_1) is continuously injected into the pipeline at a constant rate (Q_1) for a pre-estimated duration of time. Water samples are collected from a downstream location after the radiotracer is homogeneously mixed within the entire cross-section of the pipeline. The radiotracer concentration (C_2) is measured in the collected samples. The flow rate (Q_2) of water in the pipeline was calculated by using following tracer balance equation [1, 2]:

$$Q_2 = Q_1 (C_1/C_2) \qquad (1)$$

The flow rates were found to be ranging from 14.1–15.4 m^3/s with a single VT pump in operation and ranging from 24.55–27.5 m^3/s with two VT pumps in operation at each pumping unit. The uncertainty in the flow rate measurements was found to be about 3 %. The design capacity of each VT pump was estimated to be 15 m^3/s using empirical calculations. The values of the flow rates measured with radiotracers were in good agreement with the design flow rate value, thus validating the efficiency of the VT pumps. Apart from validation of the pumping efficiency of the VT pumps, the results of these measurements helped the respective industries in early commissioning of the projects, water budgeting and energy auditing leading to significant economic benefits.

2.4. Mixing or homogenization time measurement

Radiotracer techniques have been widely used to measure the mixing times in pilot scale as well as in large-scale batch systems in a variety of industries. The techniques involve the introduction of a suitable tracer into the system along with one of the components of the mix and monitor the concentration of the tracer either continuously ("in situ") using radiation detectors placed at one or more locations or take samples from a single location at regular intervals.

Another approach is to take large number of samples from different locations possibly at less frequent intervals and is statistically more representative of the process. The measurement of mixing or homogenization time using radiotracer is illustrated in following case study carried out in a glass industry [9]. Homogenization or mixing of glass melts in glass furnace and associated sub-system is one of the important parameters that governs the overall quality of the glass products. Therefore, knowledge of homogenization or mixing time is required to optimize the process, evaluate the glass quality and optimize the energy requirements.

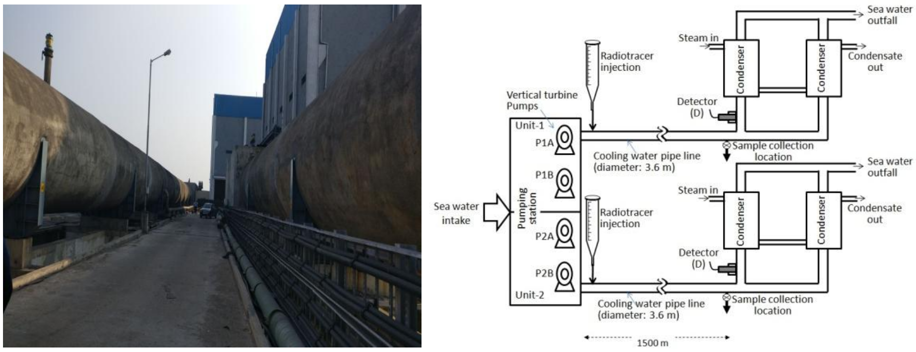

Figure 4. Photograph of the pipeline and schematic diagram of the cooling water circulation system and experimental setup for flow rate measurements [10].

Conventional methods to investigate homogeneity in glass furnaces include visual inspection, optical and compositional measurements. However, these methods have certain drawbacks such as low sensitivity to compositional fluctuation, complexity of the measurements, time consuming and lack of required accuracy. All these drawbacks can be overcome by employing radiotracer technique. A series of radiotracer investigations were carried out to measure the homogenization time in different glass furnaces and associated systems meant for production of glass sheets for use in solar panels. The schematic diagram of glass manufacturing unit for production of glass sheets is shown in Fig. 5. Lanthanum-140 (La-140) as lanthanum oxide (La_2O_3) was used as a radiotracer in the investigations. The radiotracer was mixed with silica oxide as carrier and injected into the feeders at the inlet of the furnace. Subsequently, the produced glass sheets were collected at regular intervals and the radiotracer concentration was measured at eighteen different equidistant locations in the collected sheets. The results of the measurements showed that the homogenization time of the molten glass within the unit was estimated to be 29 hours. This implied that the fed ingredients take 29 hours to melt, completely mix and uniformly distributed within the glass matrix. The results of the study helped plant engineers to control and optimize the production process, improve the quality of the glass and assess the health of the glass furnace of the manufacturing unit.

2.5. Residence time distribution measurement

Residence time distribution (RTD) is a characteristic parameter of continuous flow systems, which provides information about hydrodynamic behavior of the systems and has significant bearing on the product quality and process efficiency. Therefore, the knowledge of RTD is essential to assess the performance of the system and optimize the process. The radiotracer technique is widely used for measurement of RTD and characterizes flow in industrial process systems. The technique involves instantaneous injection of a suitable radiotracer at the inlet and monitoring its passage at the outlet or at strategically selected locations along the system [1, 2]. The collimated scintillation detectors connected to a data acquisition system set to record radiotracer concentration at a preset time interval are used for online monitoring of the radiotracer. The measured radiotracer concentration curves are treated and modeled to draw the necessary information about the flow. The technique is extensively used for troubleshooting, measurement of flow parameters, characterization/visualization of flow, optimization of operating parameters, modification of design of existing system and design of new systems. Several large scale RTD measurements using radiotracers have been carried out in India over last one decade benefiting the industry. A RTD investigation carried out in an industry is discussed below.


Figure 5. Photograph of a furnace and glass sheets

A RTD investigation was carried out in a soaker in a refinery with the main objective to identify the cause of production of more gaseous hydrocarbon fraction than the expected in the process [10]. The photograph of the soaker and the schematic diagram of the experimental setup are shown in Fig. 6. Bromine-82 as paradibromobenzene was used as a radiotracer for tracing the hydrocarbon (organic) fluid within the soaker. The radiotracer was injected at the inlet of the soaker and its concentration was measured at the inlet as well as outlet of the soaker using collimated scintillation detector connected to a data acquisition system. The measured RTD was treated and modelled using a suitable mathematical model. The results of model simulation showed existence of parallel flow paths within the soaker. The results also showed that about 36% of the process fluid spent very short time inside the soaker and can be considered as bypassed, whereas about 64% of the process fluid is backmixed within the soaker at normal operating conditions. However, at lower feed flow rates and temperature, the fraction of bypassed and back mixed flows was found to be equal.

2.6. Sediment transport

India has a long coastline of about 7515 km and there are twelve major ports situated on the coastline. Out of twelve ports, six are situated on the West Coast whereas other six are situated on the East Coast. In addition to this, there are more than 140 minor ports and other marine establishments situated along the coastline. Each port and marine project has a navigation channel and depth of this navigation channel needs to be maintained to a level of at least 12-15 meters for smooth sailing of ships. Sediments continuously move along the coast due to alongshore currents generated by the waves and tides; and get deposited in navigation channels. For maintaining the required depth of the channels, the dredging operation is carried out throughout the year or as and when required. In addition to this, the development of a new port or harbor involves huge capital dredging. The dredged sediments generated during maintenance or capital dredging needs to be dumped at a suitable location, so that it does not find its way back to the channel and obstruct sailing of ships. In addition to this, the selected site should be such that the turn-around time of the dredger is kept minimum to economize the dredging operation. In order to meet the above requirements, the knowledge of transport parameters such as the general direction of movement, extent of lateral and longitudinal movement, transport velocity, transport thickness and bed load movement rate is required [11,12].

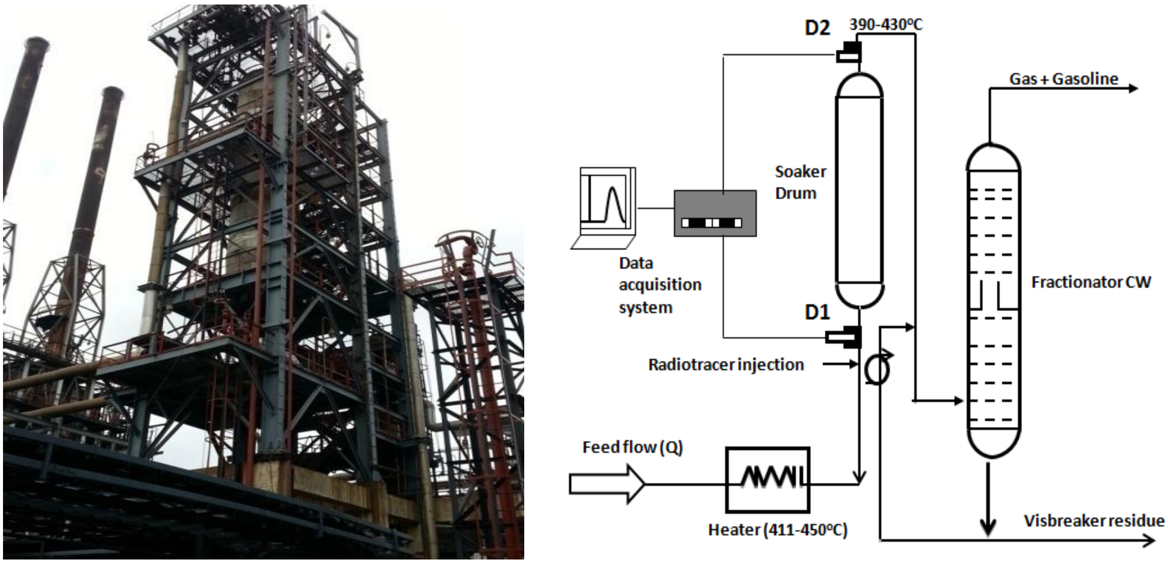

Figure 6. Photograph of the soaker and schematic diagram of the experimental setup [12]

Radiotracer techniques are commonly used to investigate sediment transport on seabed and evaluate the suitability of the proposed dumping sites. Scandium-46 (half-life: 84 days, Gamma energies: 0.89 MeV (100%), 1.12 MeV (100%)) in the form of scandium glass powder is the most suitable radiotracer for tracing sediments on seabed. The activity used in an investigation range from 75-300 GBq (2-8 Ci). The suitably prepared particulate radiotracer is injected on seabed at the proposed site using a specially designed injection system and its movement is tracked at regular intervals using waterproof scintillation detector. A photograph of the injection system is shown in Fig. 7. The concentration of radiotracer is recorded as counts per unit time and plotted as a function of latitude and longitude to obtain iso-activity contours. The iso-activity contours are analyzed to obtain various transport parameters of sediments and subsequently used to evaluate the suitability of dumping site and optimize the dumping operation. More than eighty large-scale radiotracer investigations have been carried out in all the major ports in India during last five decades. The results of a radiotracer investigation carried out at Kolkata Port, Kolkata are shown in Fig. 8 [13].

2.9. Wear and corrosion measurement

Wear and corrosion of metallic components is a common problem in industry and various areas of science and technology. Quantification of wear and corrosion rates is often required for quality control and evaluation of durability and reliability of various mechanical parts and tools. The conventional techniques such as gravimetry, profilography, micrometry, replica method etc. are commonly used for measurement of wear and corrosion rates in industry. But these techniques have low sensitivity, poor accuracy and are cumbersome to use as the components need to be dismantled for each measurement. In addition to this, they cannot be applied in all situations due to non-

Figure 7. Injection of radiotracer for sediment transport

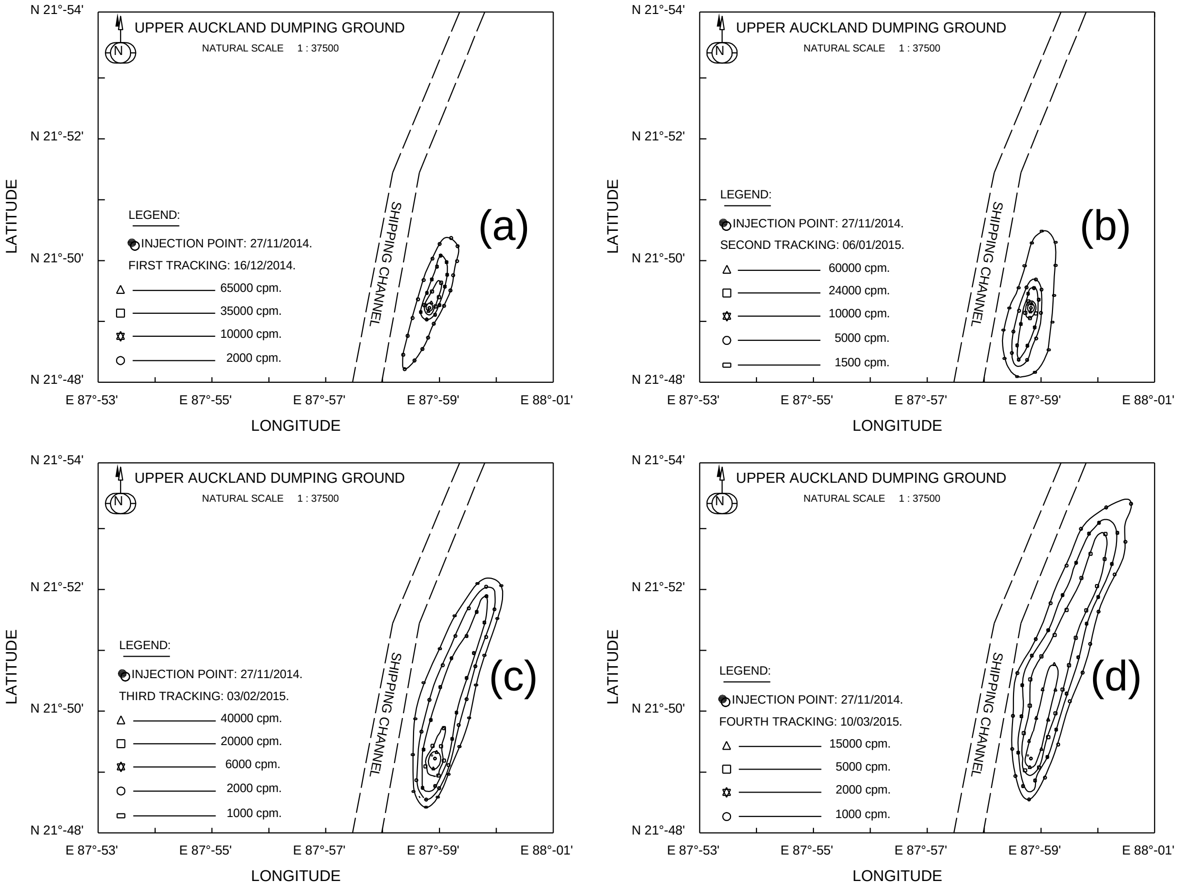

Figure 8. Isocount contours of radiotracer investigation at Kolkata Port, Kolkata [15].

accessibility. On the other hand, the radiotracer technique known as thin layer activation (TLA) technique is a highly sensitive, online, accurate, easy to use, adaptable in various situations and can be used for localized measurements [14]. It does not require elaborate safety measures, can be applied in case of commonly used materials (iron, cadmium, zinc, iridium, platinum, silver, tin, palladium, lead, tantalum), The technique is widely for wear and corrosion rate measurements in various industries such as automobile industry, power plants, process industry, oil and petroleum refineries and in many high technology areas.

The technique involves irradiation of a target material by a beam of charged particles such as proton (p), deuteron (^{2}H), helium-3 (^{3}He) and helium-4 (^{4}He) in an accelerator to produce a radioisotope within the thin surface layer (10-300 μm) of the material. The produced radioisotope depends upon elemental composition of the irradiated target material. If an iron target is irradiated with a proton beam of energy 12-13 MeV,$^{56}Fe(p,n)^{56}Co$ nuclear reaction takes place producing cobalt-56 (^{56}Co) radioisotope. ^{56}Co has a half-life of 77.3 days and emits gamma rays of energy 847 KeV (100%) and 1238.28 KeV (67 %)). Subsequently, the irradiated component is mounted in the machine and put in regular operation. During the operation, the component is subjected to wear or corrosion. Any loss of material is determined either by measuring the residual radioactivity of the radioisotope on the surface of the irradiated component or the radioactivity in debris with time. A NaI(Tl) scintillation detector coupled with a single channel analyzer or HPGe detector coupled with a multichannel analyzer (MCA) is used for measurement of the radioactivity. The measured radioactivity is plotted as a function of time and wear rate is obtained using a calibration curve. The technique has been applied for wear and corrosion rate measurements of several metallic components of technological importance.

Biswal et al. 2017 carried out a TLA study to estimate the wear rates of automobiles disc gears made of EN31 steel at different lubricating conditions [15]. Four different types of lubricants were tested for their anti-wear behavior. The gears (EN 31 steel) were irradiated with 13 MeV proton beam using BARC-TIFR Pelletron accelerator facility, Mumbai resulting in production of ^{56}Co. The irradiated gears were subjected to wear in a twin-disc tribo-tester simulating running of an engine by moving the two discs under lubricated condition (Fig. 9). Four different lubricants (TR-1, TR-2, TR-3, TR-4) were used as lubricating agents. The wear of the gear in presence of each lubricant was measured periodically by measuring the loss in radioactivity within the disc gears during the wear testing. The activity of irradiated discs was measured by gamma ray NaI(Tl) scintillation detector integrated with a multichannel analyzer. The wear testing and lubricating performance of the four lubricants was carried out as a function of various parameters such as load, speed (rpm) and temperature. Based on the results, the lubricant TR-4 was found to have the best anti-wear performance at all the parameters used.

2.10. Radioactive particle tracking (RPT) technique

The RPT technique is an advanced technique for flow visualization in laboratory and pilot-scale systems that utilizes a single gamma-emitting radioactive particle as a marker of the phase whose velocity fields are to be mapped for the liquid phase tracking in a process system, the particle should be neutrally buoyant and as smaller as possible in size (diameter). Whereas for tracking the solid phase, the particle should have same size, shape and density as the solids phase being tracked. The suitably prepared radioactive particle is introduced into the process system and its movement inside the system is tracked using an array of scintillation detectors mounted strategically around the system. The intensity of the gamma radiations emitted from the particle is recorded at a preset time interval over a predefined time duration as the particle move inside the system. Prior to the actual measurements, a calibration is performed by mounting the particle at various specified locations inside the system andrecording the gamma ray intensities recorded by the detectors. The calibration is performed at the actual operating condition at which the flow fields are to be mapped. From the calibration data and the actual measurements, the instantaneous positions of the particle as a function of time and space are determined. Subsequently, the instantaneous velocity-time series of the particle is obtained. Based on the velocity-time series, various hydrodynamic quantities such as time-averaged velocity fields, kinetic energy of fluctuations, turbulent shear stresses, Hurst exponents, residence time distributions

(RTD), dispersion coefficients, diffusivity tensor, trajectory length distributions (TLD), return time distributions, circulation patterns, etc. of the tracked phase are obtained [16].

Figure 9. Wear rate monitoring of automobile gears using TLA technique

The technique was applied to a pilot-scale bioreactor designed for wastewater treatment [16]. The wastewater is continuously fed into the bioreactor filled with a specific quantity of the media elements. Air is injected into the reactor at different angles through a sparger mounted at the bottom of the reactor. The injected air makes the media to move randomly in axial as well as radial direction within the reactor. The random movement of the media elements within the reactor causes growth of algae on the media elements facilitating deposition of the organic matter present in the wastewater. After growth of the sufficiently thick layer and death of the organic matter, the deposited layer is detached from the elements and is filtered out. The treated wastewater continuously exits from other end of the reactor. The uniform distribution and mixing of 'media' elements within the entire volume of the reactor is critical for the efficient operation of the reactor. Therefore, the RPT technique was applied to track the movement of the 'media' elements within the bioreactor. A single 'media' element was labeled with scandium-46 (^{46}Sc) radioisotope (activity: ~37 MBq) and used for tracking the movement of the media elements within the bioreactor.

Figure 10. Bioreactor and experimental setup for RPT study [21]

A photograph of the bioreactor with scintillation detectors mounted around it for recording the intensity of the gamma radiations emitted from the radioactive ^{46}Sc-labeled element during its movement inside the bioreactor is shown in Fig. 10. After analyzing the recorded rata, several flow abnormalities were identified, velocity fields were obtained and detailed flow of the media elements within the reactor was visualized. The flow abnormalities were primarily attributed to the poor design of the air-sparger used in the reactor. Based on the results of the study, several modifications in the design of the air-sparger were suggested and subsequently implemented. After implementing the modifications, the efficacy of the reactor improved significantly leading to substantial technological and economic benefits to the industry.

3. Conclusion

- Bhabha Atomic Research Centre has good infrastructure and expertise for application of radiotracer technology in industry. The technology is well-developed and services have been routinely provided to the Indian industry for troubleshooting, measurement of process parameters and process visualization and optimization on commercial basis. The industry has been enormously benefited from the application of radiotracer technology and the cost to benefit ratio in different applications varies from 1:10 to 1:5000.
- In addition to the routine commercial services provided to the industry by BARC, in-house radiotracer laboratories have been established in various academic institutes and R&D departments of the public/private sector companies for their own in-house applications. Such laboratories are established as per the norms and with license from the competent regulatory agency of the respective countries.
- The transport and use of radiotracers is well regulated and supervised by competent radiation protection and supervisory agencies. Thus do not cause any radiation hazards to public and users.
- The demand for application of radiotracer technology in the Indian industry, though growing, but is currently confined to only a few well-informed industries and not commensurate with the size of the Indian industry. Considering the size of the Indian industry, there is good scope for wider application of radiotracer techniques and can be effectively used to minimize shut down times of industrial plants; and improve industrial productivity and product quality thus leading to increased revenues for the industry.

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Chapter 2: Application of isotope hydrological techniques in water resources

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Abstract: *Water is a precious national resource requiring efficient management and conservation. The task is a challenging one in Indian context, due to the diverse climatic and hydrologic ecosystems. Isotope hydrology activities of Radiochemistry and Isotope Group of BARC have contributed significantly to the management and conservation of water resources in water scarce regions by implementing isotope technologies. In isotope hydrology, ratios of isotopes of elements like Oxygen and Hydrogen of water molecule as well as Nitrogen, Carbon and Sulphur of dissolved salts are measured to establish the source of water, contaminants and assess the sustainability of water resources. This information is used to devise strategies for better water conservation and also to identify and isolate the contaminant sources. Only in very specific and localized studies, radioactive tracers produced in a nuclear reactor are used. Using isotope technology, recharge zones of several drying springs in mountainous regions of India have been identified. Construction of suitable artificial structures at the identified zones (altitudes) helped in enhancing the discharge rate and extending the duration of spring flows. Precise information on groundwater recharge condition, interconnections among aquifers and groundwater contamination has also been obtained through isotope technology. This information is critical to strategize plans for improving the groundwater resources in drought prone as well as contaminated regions of India. This chapter showcases the BARC's endeavours towards successfully developing and implementing isotope technology in various parts of India, that provide solutions to key challenges in water sector.*

1. Introduction

The water was present in our solar system from the beginning and was formed by the thermonuclear fusion process that produced the elements and their compounds. The total amount of water contained on Earth is estimated to be about 0.4% by volume, sufficient to form a sphere of ice with a diameter of almost 2500 km and a volume of 8.2×10^{9} km^{3}. However, all this water is not free but is bound in rocks and minerals within the crust and mantle. The amount of free water (hydrosphere) is estimated to be 1.4×10^{9} km^{3}, i.e. 17% of the total water on Earth. Among this reservoir, 96% is stored in the oceans as saline water and only 2.5% is of desired quality that human can use. 79% of this freshwater reserve is trapped in ice caps and glaciers, which are difficult to access, and the rest in groundwater (20%) and surface water (1%) [1-2]. A pictorial representation is shown in Fig. 1. Oceans are the ultimate source of all fresh waters on the earth. Evaporation at ocean surface forms clouds, which then move to continent side owing to pressure difference created by unequal heating of the atmosphere. The clouds condense at higher altitudes to form liquid water/snow. This traversing path of water molecules in the hydrological cycle is accompanied with variation in isotopic composition at every stage, which depends on the meteorological conditions such as temperature, humidity, state of equilibrium of the process, amount and intensity of rainfall and geographic locations such as northern or southern hemisphere, latitude, altitude etc. The ideal tracer for tracing water in the hydrological cycle would be water itself, which is a great challenge since it involves differentiation of different water molecules. However, this can be achieved through isotopes. Chemically water molecule (H_2O) is made up of two atoms of hydrogen and one atom of oxygen. But, hydrogen has three naturally occurring isotopes, viz., ^1H, ^2H (D) and ^3H (T), and oxygen also has three isotopes, viz., ^{16}O, ^{17}O and ^{18}O. Though several isotopic species of the water molecule are possible, $H_2{}^{16}O$ (99.76%), $HD^{16}O$ (320 ppm) and $H_2{}^{18}O$ (2040 ppm) are more relevant to the isotope hydrology because of their higher abundance [3].

Isotope hydrology is the science that uses relative distribution of isotopes of H and O atoms in water molecule to infer processes that are otherwise difficult by conventional techniques. It is a comparatively young scientific discipline started around 1950s when it was first realized that the methods of nuclear physics and chemistry for the detection of isotopes could have valuable applications in hydrology. The conventional tools of isotope hydrology are the isotopes of the constituent elements of the water molecule (H_2O) itself, i.e., the isotopes of hydrogen and oxygen. However, later on, many more isotopes (of dissolved salts) were added including injected radioactive tracers and some non-isotope tracers (dissolved noble gases). The isotope hydrology may now be defined as “the application of environmental isotopes and tracers to study the source, origin, distribution and dynamics of water in various components of hydrosphere” [3].

The application of isotopic methods and isotopic data in hydrogeological studies noted a fast increase in the last few decades. The isotopes being used in hydrological sciences are both stable (^2H, ^3He, ^{11}B, ^{13}C, ^{15}N, ^{18}O, ^{34}S ^{37}Cl, ^{87}Sr etc.) and radioactive (^3H, ^{14}C, ^{36}Cl, ^{32}Si, ^{39}Ar, ^{85}Kr, ^{226}Ra, ^{222}Ra, ^{238}U, ^{235}U, and ^{232}Th) [4]. The stable isotopes are used mainly for determining the origin of specific solutes in groundwater, geochemical evolution in aquifers, processes controlling the solute mobilization and transport, whereas radioisotopes are primarily used to define the relative or absolute age of water in an aquifer. The calculated age gives the evidence of the residence time of groundwater (saturated zone) in an aquifer once it has passed through the unsaturated zone. Typical hydrological investigations include aquifer-aquifer interconnection (aquifer: water containing geological formation), surface water-groundwater interconnection, source of groundwater salinity and pollution, origin of geothermal waters, efficacy of artificial recharge, dynamics in lakes, source and origin of the groundwater, aquifer dynamics and sustainability, paleochannels and climate investigations, etc. In some cases, mainly in local scales, injected tracers are used to estimate the groundwater velocity and flow direction [3-5].

A variety of well-established and field-verified isotopic techniques are available, which are useful tools with proven technological and economic benefits for water resource assessment, development, and management. It is important to note that isotope studies are not expensive and that a single analysis can yield a considerable amount of information on the hydrological process, as compared to costlier classical investigations. This article provides a gist of principles of isotope hydrology, measurement techniques and some selected applications.

2. Principles of isotope hydrology

The application of isotopes in hydrology is achieved through tracing the evolution of a water mass from its origin as precipitation, through its recharge processes, and ending at its appearance in an aquifer. The main processes of the hydrological cycle (evaporation and condensation) contribute to the variations in the isotopic composition of water molecules. This happens because of isotope fractionation, which is defined as the partial separation of isotopes of an element between two or more chemical species or phases, leading to changes in the isotopic composition of the element in two reservoirs. The two basic fractionation mechanisms are; Equilibrium isotope fractionation, which is due to the difference in bond energies of isotopes in compounds and Kinetic isotope fractionation, which is due to differences in average velocity or reaction rates of different isotopes. Both mechanisms depend only on the mass of the isotope and hence are called mass-dependent fractionation [6].

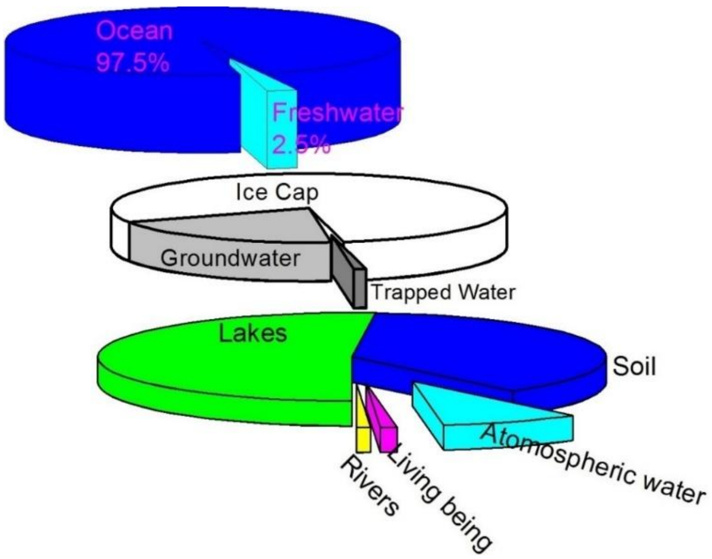

Figure 1. Global water distribution

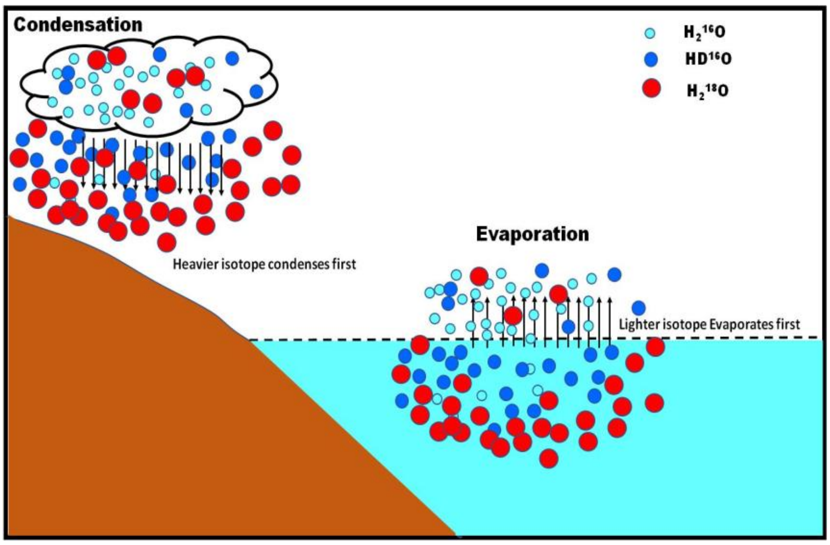

Figure 2. Schematic of isotope fractionation

2.1. Equilibrium isotope fractionation

It controls the distribution of isotopes in systems that approach the thermodynamic equilibrium. Isotopes distribute themselves among compounds to minimize the energy of the system. The sensitivity to mass comes in through the vibrational modes of inter-atomic bonds. It should be noted that isotope fractionation will only occur in systems that do not proceed to completion. The magnitude of an isotope effect is expressed as an isotope fractionation factor (α), which is defined as the ratio of the heavy to light isotope in the product divided by the ratio of the heavy to light isotope in the reactant. Condensation is an equilibrium process and occurs at 100% relative humidity whereas evaporation normally occurs under non-equilibrium conditions and is controlled by kinetic isotope effects. The exact fractionation value depends on factors such as relative humidity and turbulence at the air-sea interface [3-5].

2.2. Kinetic isotope fractionation

This occurs in fast, incomplete, or unidirectional processes like evaporation, diffusion, and biological reactions. For e.g., the molecules with light isotopic species will diffuse faster in the gas phase leading to fractionation. Kinetic effects are much larger than equilibrium effects and depend only on the forward reaction rates. Of all the various reasons for isotopic fractionations, the most important one is the higher volatility of the lighter $H_2{}^{16}O$ compared to the heavier species. This makes vapor lower in deuterium by ~8 % and ^{18}O by ~0.9 % relative to liquid water. Therefore, the vapor is always depleted in heavy isotopes relative to the liquid and the condensate is always enriched in heavier isotopes relative to the vapor. A schematic diagram of the isotope fractionation is shown in Fig. 2 [3-5].

Fractionation also occurs during chemical changes due to difference in the vibrational frequency of chemical bonds. The lighter isotope is more reactive; therefore, it is concentrated in reaction products, enriching reactants in the heavier isotope. For example, during the acid hydrolysis of calcium carbonate, the product calcium hydroxide is enriched in ^{16}O and CO_2 enriched in ^{18}O due to greater ease with which C-^{16}O bonds in the reactant carbonate can be broken.

2.3. δ definition

The abundance of ^{18}O in the terrestrial materials ranges from 1900 to 2100 ppm and average is close to 2000 ppm. Similarly, the abundance of ^{2}H in sea water is about 350 ppm. It is difficult to determine accurately the absolute isotopic content in every compound in routine analysis and in hydrological studies, it is sufficient to know the relative abundance with respect to a standard. Therefore, the isotope data is expressed in relative terms and is determined easily with great accuracy by an isotope ratio mass spectrometer. The relative deviation denoted by δ (delta) value is defined as [7];

$$\delta \quad = \quad \left(\frac{R - R_{std}}{R_{std}}\right) \quad \times 10^{3}$$

where *R* represents the isotope ratio of a sample ($^{2}H/^{1}H$, $^{13}C/^{12}C$, $^{18}O/^{16}O$, etc.) and R_{std} represents the corresponding ratio in the standard. The δ value is very small, so it is expressed in parts per thousand (per mil, ‰). A sample with $\delta^{18}O$ value of +10‰ is thus enriched in ^{18}O by 10 ‰ (or 1%) relative to the standard and a value of -5 ‰ signifies that the sample is depleted in ^{18}O by 5‰ (0.5%) compared to the standard. The meteoric waters (i.e. atmospheric moisture, precipitation, groundwater and surface water derived from them) are mostly depleted in the heavy isotopic species compared to the oceans, so the δ values are negative.

3. Stable isotopes

In 1961, Harmon Craig found that the changes of ^{18}O and ^{2}H contents in meteoric waters are fairly well correlated, and the equation to best fit line of $\delta^{18}O$ and $\delta^{2}H$ data of global precipitation is found to be; $\delta^{2}H = 8*\delta^{18}O + 10$. This line is referred as Global Meteoric Water Line (GMWL), which is essentially made up of many Local Meteoric Water Lines (LMWL) [8], which is updated using more number of samples covering the globe as $\delta^{2}H = 8.17*\delta^{18}O + 11.27$. The plot of $\delta^{18}O$ versus $\delta^{2}H$ is used to understand the impact of various physico-chemical processes on stable isotopic composition of water in an area (Fig. 3). The isotopic variations are related to geographical parameters such as latitude, altitude and distance from the coast. The isotope systematics in precipitation indicated, i) a gradual decrease of the heavy isotopic concentration when going from lower to higher latitude (latitude effect), ii) a decrease in $\delta^{2}H$ and $\delta^{18}O$, when going from coast to a continental areas (continental effect), iii) seasonal variation of $\delta^{18}O$ and $\delta^{2}H$ is related to seasonal variation in temperature (seasonal effect), iv) decrease in $\delta^{18}O$ and $\delta^{2}H$ content with increasing altitude (altitude effect), typical gradients in $\delta^{2}H$ and in $\delta^{18}O$ are 1.5 to 4‰ and 0.2 to 0.5‰ per 100 m respectively, v) negative correlation between $\delta^{18}O$ and $\delta^{2}H$ and the amount of rainfall (amount effect), has typical depletion of ~1.5‰ in $\delta^{18}O$ per 100 mm of rainfall [5-7].

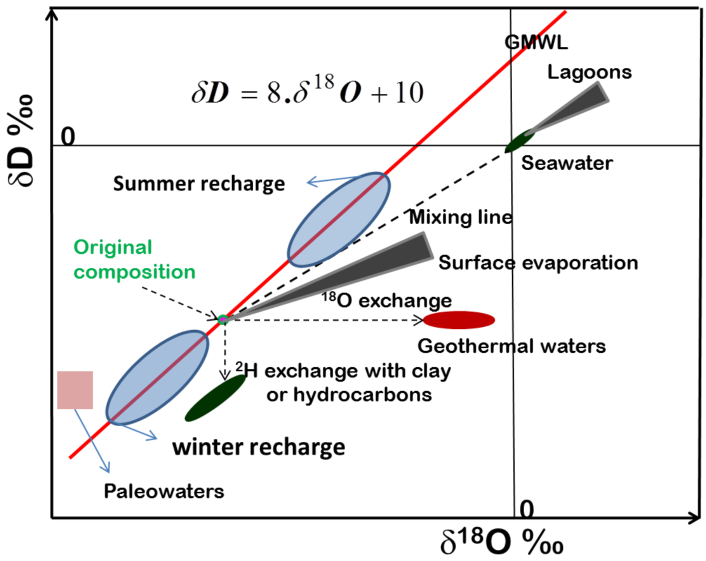

Figure 3. Variations in $\delta^{18}O$ and $\delta^{2}H$ values from the original composition on reference GMWL due to various physicochemical processes

The $\delta^{2}H$ vs $\delta^{18}O$ relationship for precipitation in any given region however often differs from the global equation. In order to relate the isotopic composition of any water sample to GMWL, deuterium excess parameter ($d = \delta^{2}H - 8\ \delta^{18}O$) is used, which is a measure of the relative proportions of $\delta^{18}O$ and $\delta^{2}H$ contained in water. This parameter infers the physical conditions such as air temperature, humidity and surface temperature of the source area responsible for vapor transport to the site of precipitation.

The variations in isotopic content of the meteoric waters are typically in few ppm, hence a sophisticated mass spectrometric equipment is used to routinely measure such small differences in isotopic contents of water samples with respect to a standard. The universally accepted standard for reporting stable isotope compositions of natural waters for hydrogen and oxygen isotopes is the Standard Mean Ocean Water (SMOW). It is a logical and natural choice for the standard since all fresh water on the planet is derived from the oceans, and being a very large water body there would be no appreciable change in the isotopic composition with time. The natural isotopic abundances, standards used for some of the common isotopes in hydrology along with their application are given in Table 1.

Table 1. List of isotopes of hydrological significance, references and their applications [3]

Isotope	Ratio	% Abundance	Reference	Measured phases	Applications
^{2}H	$^{2}H/^{1}H$	0.015	VSMOW	H_2O, CH_4	Origin of water
^{13}C	$^{13}C/^{12}C$	1.11	VPDB	CO_2, Carbonates	Pollution and dating
^{15}N	$^{15}N/^{14}N$	0.366	Air N_2	N_2, NH_4NO_3	Pollution marker
^{18}O	$^{18}O/^{16}O$	0.204	VSMOW	H_2O, CO_2, SO_4^{2-}, NO_3^{-}	Origin of water
^{34}S	$^{34}S/^{32}S$	4.21	CDT	SO_4^{2-}, H_2S	Salinity & aquifer redox condition
^{37}Cl	$^{37}Cl/^{35}Cl$	24.23	SMOC	Saline waters	Source of pollution
^{87}Sr	$^{87}Sr/^{86}Sr$	07.00	USGS *Tridacna*	Solution	Provenance of water
^{11}B	$^{11}B/^{10}B$	80.1	NISTRM 951	Solution	Source of pollution

Sampling for oxygen-18 and deuterium does not require any filtration or preservation. A 50 mL, double capped, glass or polyethylene bottle is filled directly from the source (at site) in such a way that there is no air bubble trapped inside and tightly capped. During sampling, storage and transportation to the laboratory; special care should be taken to avoid evaporation of the sample.

Commonly used equipment for the stable isotope measurements is Isotope Ratio Mass Spectrometer (IRMS). The mass spectrometer is attached to a multiflow unit, which is an automated sample injection system for the measurement of δD and $\delta^{18}O$ in aqueous samples. For $\delta^{18}O$ analysis 200 µl of aqueous sample is equilibrated with a gas having the composition of 5% CO_2 in Helium at two bar pressure under $30^{0}C$ for 6 hours. After the equilibration, the headspace gas is injected into the mass analyser for isotopic ratio determination. For $\delta^{2}H$ measurement, approximately 0.2 ml of the water sample is equilibrated with mix gas (10% H_2 in He) at two bar pressure in presence of Hokko bead platinum catalyst. Equilibration temperature is maintained at 30˚C for 90 minutes. The equilibrated gas is then injected into the mass analyser. The measured values are then normalized on VSMOW/SLAP scale. The 2σ precision of measurement for $\delta^{18}O$ is ± 0.1 ‰ and $\delta^{2}H$ is ± 0.5 ‰ [9].

4. Radioisotopes

4.1. Tritium (T or ^{3}H)

The radioactive isotope tritium (^{3}H) can be used for dating very young groundwater (less than 50 years). Natural tritium is formed in the upper atmosphere by the bombardment of nitrogen with fast neutrons. Tritium then combines with oxygen to produce tritiated water (^{3}HHO) and enters the hydrologic cycle. Tritium decays to a stable isotope of helium (^{3}He) by beta (β^{-}) emission. The production of tritium and its decay in the equation are shown below [10];

^{14}N + neutron → ^{12}C + ^{3}H

$^{3}H \rightarrow {}^{3}He + \beta^{-}$

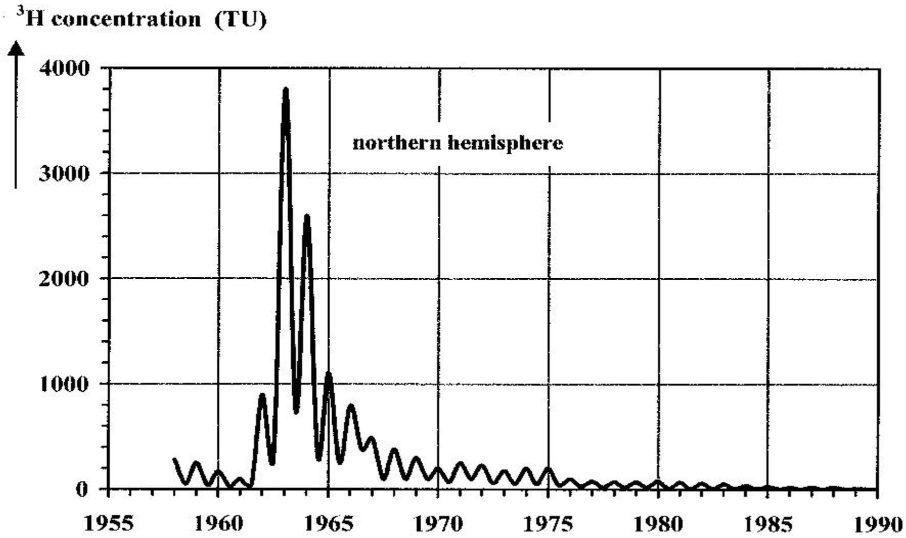

Figure 4. Temporal variation of ^{3}H content in precipitation over the continental surface of the Northern hemisphere

Tritium concentrations are represented in tritium units (TU), where one tritium unit is equal to one molecule of ^{3}H per 10^{18} molecules of ^{1}H and has an activity of 0.118 Bq/kg (3.19 pCi/kg). Tritium is typically measured by a liquid scintillation counter after pre- enrichment. The enriched sample is mixed with a scintillation mixture of a solvent, emulsifier, and solute. The electrons from tritium decay excite the solvent, which transfers its energy to the solute resulting in scintillation (emission of light photons). The light pulses are detected and counted. Though the natural production of tritium in the atmosphere is very low, the tritium activity in the atmosphere increased mainly during 1960s from the atmospheric testing of thermonuclear bombs (Fig. 4). In the last four decades since the last major tests, thermonuclear bomb tritium has been greatly attenuated by oceans and the levels are now approaching that of natural atmospheric production. As a consequence, the quantitative interpretation of groundwater mean residence time is difficult and involves complex calculations. However, the tritium data is mostly commonly used for qualitative interpretations. Depending upon the tritium levels in measured water sample following ages can be inferred [3].

<1 TU	Sub-modern – recharged prior to 1952
1 to ~4 TU	Mixture between sub-modern and recent recharge
5 to 15 TU	Modern (<5 to 10 years)
>30 TU	Considerable component of recharge from 1960s or 1970s
>50 TU	Dominantly the 1960s recharge.

4.2. Carbon-14

Radiocarbon (^{14}C), a cosmogenic isotope of carbon with a half-life of 5730 years, is useful for age dating as well as for tracing hydrologic processes. ^{14}C is formed in the atmosphere when neutrons interact with ^{14}N (nitrogen) atom as shown below [9];

^{14}N + neutron $\rightarrow$ ^{14}C + proton

Subsequently, the ^{14}C reacts with atmospheric oxygen to produce CO_2 and enters into the hydrological cycle as bicarbonate (HCO_3^-), either by reacting with moisture or through root respiration. Much of the ^{14}C has been added to the atmosphere due to the nuclear bomb tests during the 1960s. Depending up on the time elapsed by groundwater in aquifers the ^{14}C activity decreases, and this decrease in activity is used to infer the residence of groundwater.

For radiocarbon sampling, dissolved inorganic carbon (DIC) is collected in the form of $BaCO_3$ precipitate from about 100 L of water using saturated carbonate free $BaCl_2$ solution. In order to convert all DIC into carbonate form, the pH of the water is raised to >10 by adding sodium hydroxide (NaOH). $BaCO_3$ is precipitated by adding saturated solution of $BaCl_2$. To fasten the settling of the $BaCO_3$ precipitate, Ferrous Ammonium salt (as coagulant) along with poly acrylamide (as settler) is added. The $BaCO_3$ precipitate is collected after decanting. This $BaCO_3$ precipitate is treated with phosphoric acid to generate CO_2, which is then trapped using cryostat (liquid nitrogen). The trapped CO_2 is stored in a cylinder and kept for 30 days for radon to decay. The gas is then passed through carbon absorber and scintillator mixture and counted in a liquid scintillator counter. The ^{14}C activity is reported as percent modern carbon (pMC). The minimum detection limit for ^{14}C is 1 pMC. The typical ages measured by this technique are up to ~ 40,000 years. Very low levels of radiocarbon are measured using Accelerator Mass Spectrometry (AMS). This can allow estimation of groundwater ages up to 80,000 years [9].

Direct estimation of groundwater age based on measured ^{14}C data is not advised since the initial ^{14}C activity can be changed by many geochemical processes mainly from the dissolution of the dead carbon (fossil carbon) present in the aquifer. Therefore, the groundwater ages need to be corrected according to aquifer conditions to arrive at most reliable values. In addition to ^3H and ^{14}C, there are many naturally occurring radio isotopes that are used for both age dating as well as other hydrological applications. The list of the commonly used radioisotopes in hydrology is given in Table 2.

Table 2. Environmental radioisotopes used in hydrology [3]

Isotope	Ratio	% Abundance	Half life	Applications in hydrology
Tritium (^3H)	$^3H/^1H$	10^{-16}	12.3 years	Young groundwater dating
Carbon (^{14}C)	$^{14}C/^{12}C$	10^{-10}	5730 years	Old groundwater dating
Chlorine-36 (^{36}Cl)	$^{37}Cl/^{35}Cl$	10^{-13}	3.1×10^5 years	Very old groundwater dating
Radium-226 (^{226}Ra)	Daughter product of ^{238}U series		1600 years	Submarine groundwater discharge (SGD) and geothermal investigation
Radon-222 (^{222}Rn)	Daughter product of ^{238}U series		3.8 days	Groundwater dating, surface water infiltration, SGD

5. Stable isotopes of dissolved species

Besides stable isotopes of water, ^2H and ^{18}O, there are other stable isotopes that are used in hydrological studies, such as, ^{13}C, ^{15}N and ^{34}S, which occur as dissolved compounds in the form of carbonates, nitrates and sulfates respectively. These isotopes are measured using mass spectrometers in respective gaseous forms and their isotopic variations are useful in not only source identification but also in understanding the geochemical processes. The typical ranges of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ in different sources are shown in Fig.5 (a-c) [3].

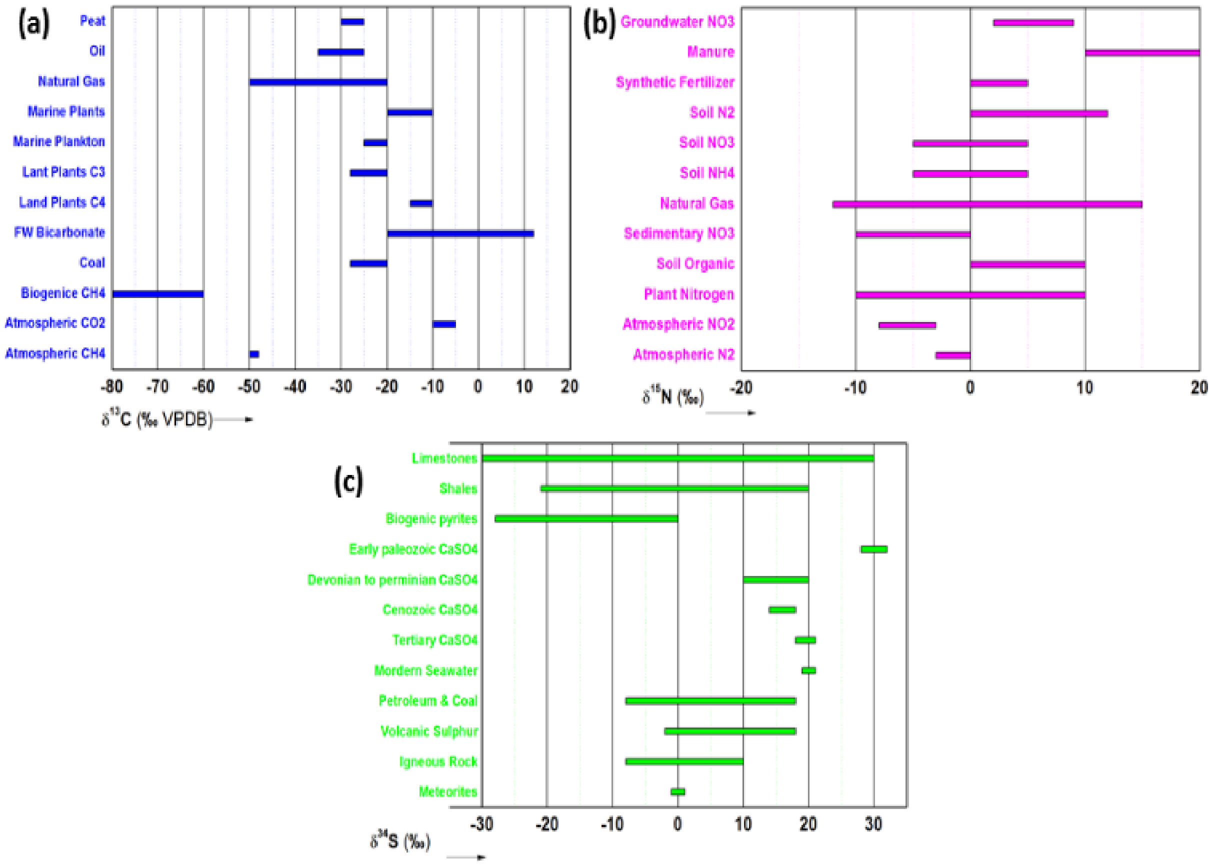

Figure 5. (a) $\delta^{13}C$, b) $\delta^{14}N$ and c) $\delta^{34}S$ distribution in selected natural compounds

6. Applications

Isotope applications in hydrology are based on tracer concept in which naturally occurring isotope (radioactive or stable) are used to understand the hydrological processes during their natural circulation in a hydrological system. These applications are highly diverse and used for implementing water policy, mapping aquifers, conserving water supplies, assessing sources of water pollution, and increasingly are used in eco-hydrology to study human impacts on all dimensions of the hydrological cycle and ecosystem. A few important applications are briefed in this article taking some selected case studies.

6.1 Groundwater recharge

The importance of groundwater recharge studies has grown manifold in the past few decades due to rapidly rising concerns over the impacts of climate change and human interferences on the consumption of groundwater resources. A clear understanding and knowledge is important for better sustainable management of groundwater resources. However, understanding spatial influence on groundwater recharge in inherently complex multi aquifer systems is a challenging task and isotope tools are proved to be useful regarding these studies. The isotope value of groundwater commonly reflects the origin of recharge and temperature of precipitation that recharged the groundwater. Mean elevation of precipitation where the recharge occurs may be estimated with the help of the local vertical isotopic gradient of precipitation which can be obtained from the weighted mean isotopic data and elevation data of precipitation [11].

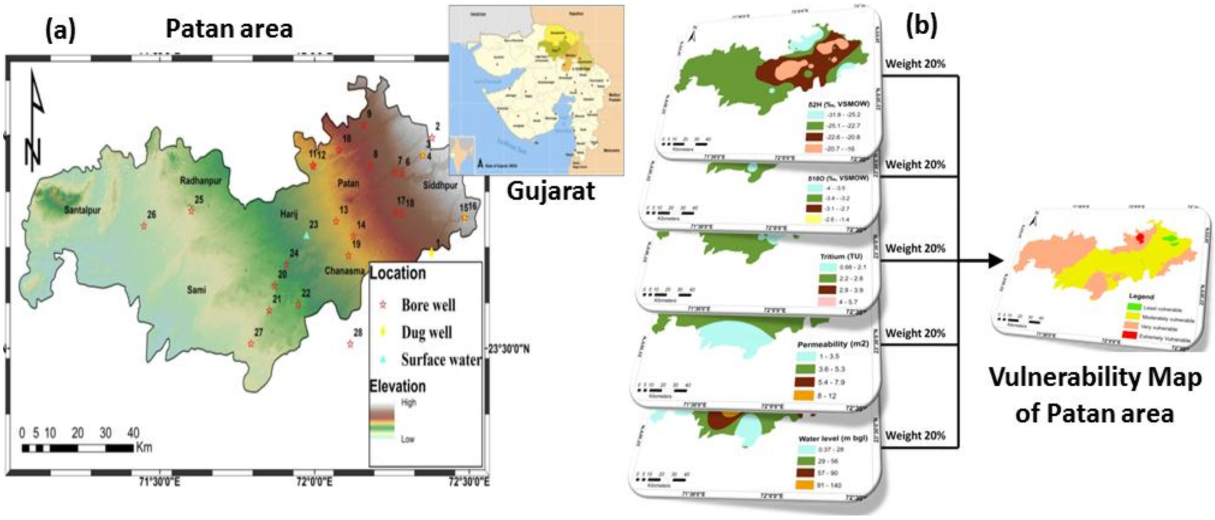

Figure 6. (a) Study area of Patan district, Gujarat and b) vulnerability map

An isotope investigation was taken up in over-exploited regions of Gujarat with an objective to identify the most potential zones of groundwater recharge and interactions between multiple water-bearing zones (Fig. 6a). The results showed that groundwater exists in mainly three zones dominantly recharged by meteoric source. The top shallow zone (up to 150 m depth) is mostly brackish to saline with very little recharge from rainwater (3-12%) whereas the confined intermediate and deep zones receive recharge from foot hills of Aravali. Age dating of groundwater samples indicates younger age (about 1500 years) to deep groundwater samples in the north-eastern part which increases to > 6500 years towards south-western part of the study area, indicating the potential zones for groundwater recharge. The isotope results when integrated with chemical and lithological information provided insights into the vulnerability of groundwater towards contamination (Fig. 6b). Groundwater recharge studies have been carried out in semi-arid and arid zones of India such as Jaisalmer (Rajasthan), Chitradurga (KA), Delhi, Srikakulam (A.P.), Nalgonda (Telangana), etc.

6.2 Groundwater contamination

Clean water in India is mostly derived from groundwater, which is being impacted by many natural and anthropogenic activities. The arsenic and fluoride contamination of groundwater is mainly geogenic in nature, while nitrate contamination and salinity can be mainly attributed to anthropogenic activities. Uranium contamination has also been reported in some parts of India especially from northwestern parts and it is mostly attributed to geogenic sources [12-16]. Iron is another contaminant of geogenic source, but is a lesser health hazard. Localized pockets of high iron are observed in the states Bihar, UP, Kerala and North Eastern States. An isotope investigation was carried out in Ilkal area of Bagalkot District, Karnataka where growing cases of dental and skeletal fluorosis in residents were reported (Fig. 7a). The possible source of fluoride in this region is fluoride bearing minerals present in granitic rocks which could have contributed either by weathering of rocks in the subsurface or by rock polishing industrial wastes (Fig. 7b). Fluoride levels ranged from 0.1 to 6.5 mg/L with more than 75% of the samples contaminated. Isotope results indicated that affected groundwaters are evaporated in nature, and more so near the surface water bodies (Fig. 7c). Environmental tritium data (Fig. 8d) further helped in delineating groundwater zones where fluoride contamination is derived from anthropogenic inputs (rock polishing industries) and natural input (rock weathering) [14-15]. Fluoride contamination studies were also carried out in Talchir (Odisha), Nalgonda (Telangana), Jaipur (Rajasthan) and Bathinda (Punjab), etc.

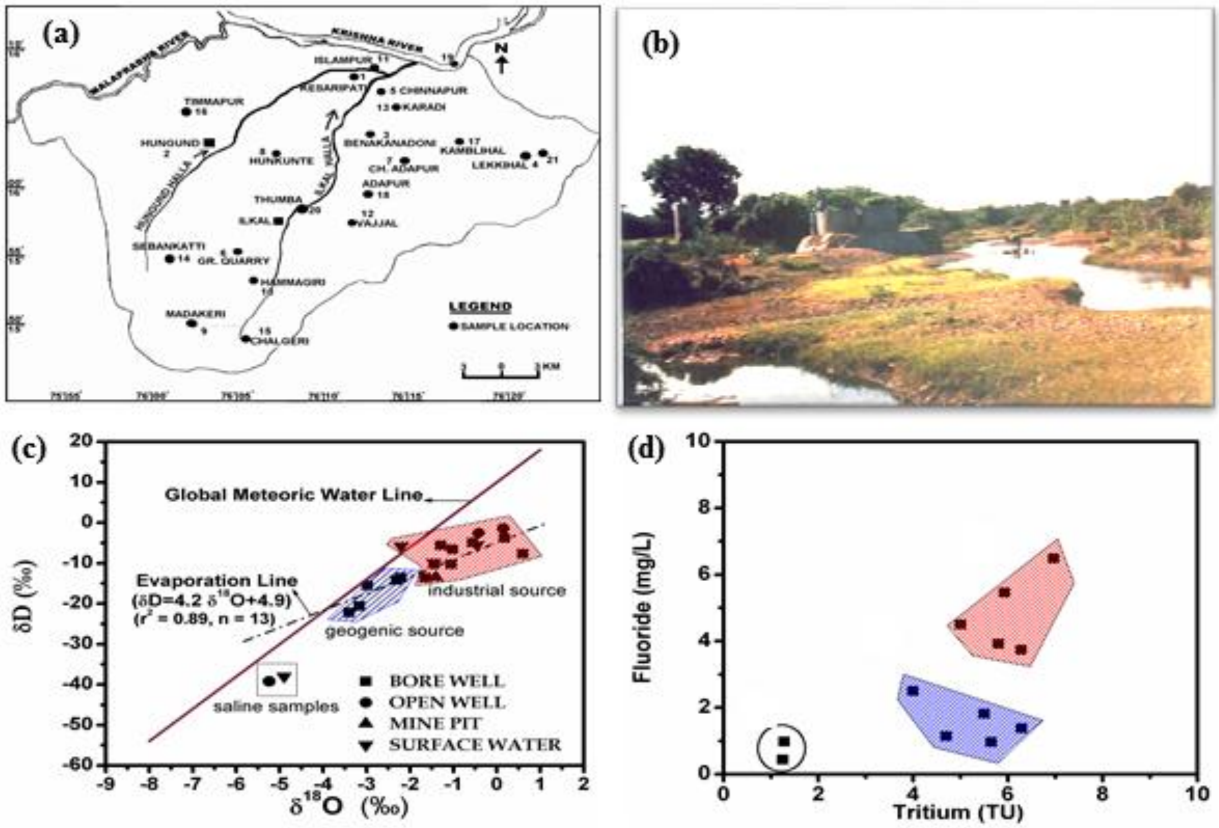

Figure 7. (a) Fluoride affected Ilkal area, b) rock power dump site, c) δ^2H versus δ^{18}O plot and d) F^- vs tritium plot

6.3 Seawater intrusion

The possible causes for groundwater salinity are dissolution and flushing of dry salts by precipitation, evaporative enrichment, mixing of saline water and connate sea water or fossil sea water. These processes are clearly differentiated using isotope signatures of waters. In order to determine the nature and extent of groundwater salinization in Chennai City, an isotope study was carried out in alluvial and hard rock zones of coastal Tiruvanmiyur aquifer. The overall hydrochemistry of most of the groundwaters is generally fresh with electrical conductivity (EC) < 1500 μS/cm. However, a few samples from semi-confined aquifer are brackish to saline with EC ranging up to 30,000 μS/cm. Isotopic analysis of the most of the fresh water samples of unconfined and semi-confined zones indicated their meteoric origin without significant evaporation prior to infiltration (sample data fall on meteoric water line), whereas samples of some places showed slightly enriched stable isotopic values and they lie away from the local meteoric water line. The isotopic enrichment and brackish quality of these groundwaters could be due to the contribution from evaporated surface water such as backwater. The positive correlation between the salinity of the waters and their δ^2H and δ^{18}O values have been attributed to mixing between meteoric water and sea water or saline brines that have evolved through seawater modification or seawater intrusion. Chloride and $\delta^{18}O$ correlations indicated that the salinity is mostly attributed to dissolution of aquifer sediments. The brackish and saline waters are found to be about 11000 and 7000 years old respectively. Based on the isotope, geochemical and lithological information a conceptual map was prepared depicting the groundwater flow in this aquifer (Fig. 8). Many coastal regions were studied for groundwater salinization problem including, Kudankulam, Nagapattinam and Minjur (TN), Midnapore (WB), Vishakapattinam (AP), Palgarh (MH), Delang-Puri (Odisha). Similarly inland salinity is also studied using isotope techniques in Purna basin (MH), Haryana and Punjab [17-18].

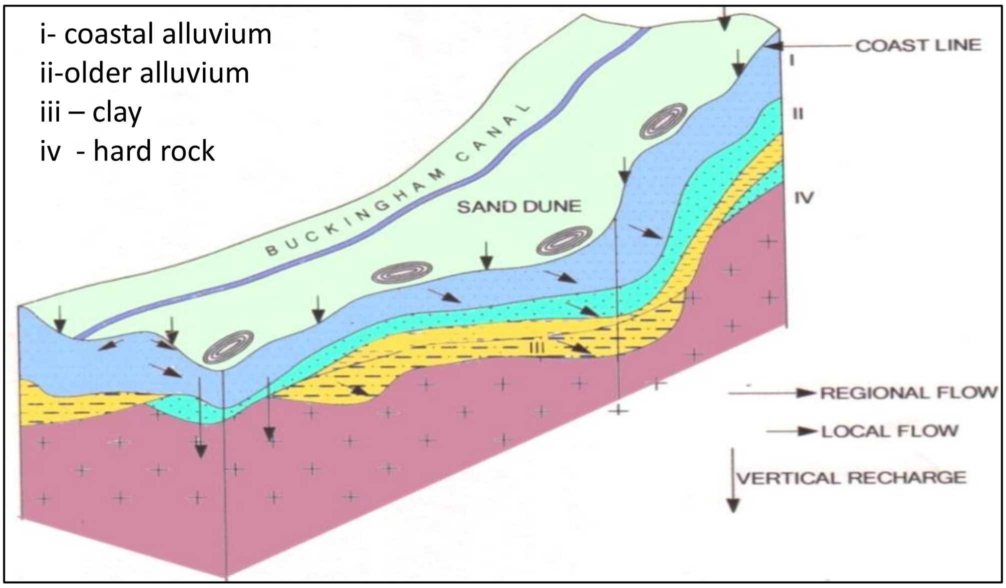

Figure 8. Schematic groundwater flow diagram of Chennai city, Tamil Nadu

6.4. Recharging drying springs

In Uttarakhand, currently 30% of the springs have almost dried up, and an additional 45% of the springs are on the verge of drying up, affecting approximately 60% of the population in mountainous villages. Most of the villages have been classified as water-scarce and many more in the verge of becoming water scarce. The springs are mainly fed by subsurface water, which is reduced due to deforestation in recharge areas, reduction in rainfall infiltration due to artificial structures such as roads and buildings, disturbance in the source of the distribution, poor rainfall etc. The recharging of spring water can be achieved through artificial rainwater harvesting structures. In order to identify the altitude of most potential recharge zones to the springs, isotope investigation was carried out covering about 50 springs in this state. A typical site map is shown in Fig. 9a. The initial observations from spring discharges and stable isotope data indicated that the springs are mainly precipitation recharged and are highly seasonal. The altitude of recharge to springs is estimated using the altitude effect, which was computed by measuring the stable isotope content of rainwater samples from different altitudes in the same valley. A typical plot representing altitude effect (0.42‰ $\delta^{18}O$ per 100m for Nakuri Gaad area) is shown in Fig. 9b. Based on the identified recharge altitudes, rainwater harvesting structures were recommended and constructed at the sites (Fig. 9c-f). A great improvement in spring discharges (3 to 5 times) and duration are observed (Fig. 9 g&h). Similar studies were conducted in Himachal Pradesh, Jammu and Kashmir, Sikkim states of India [19].

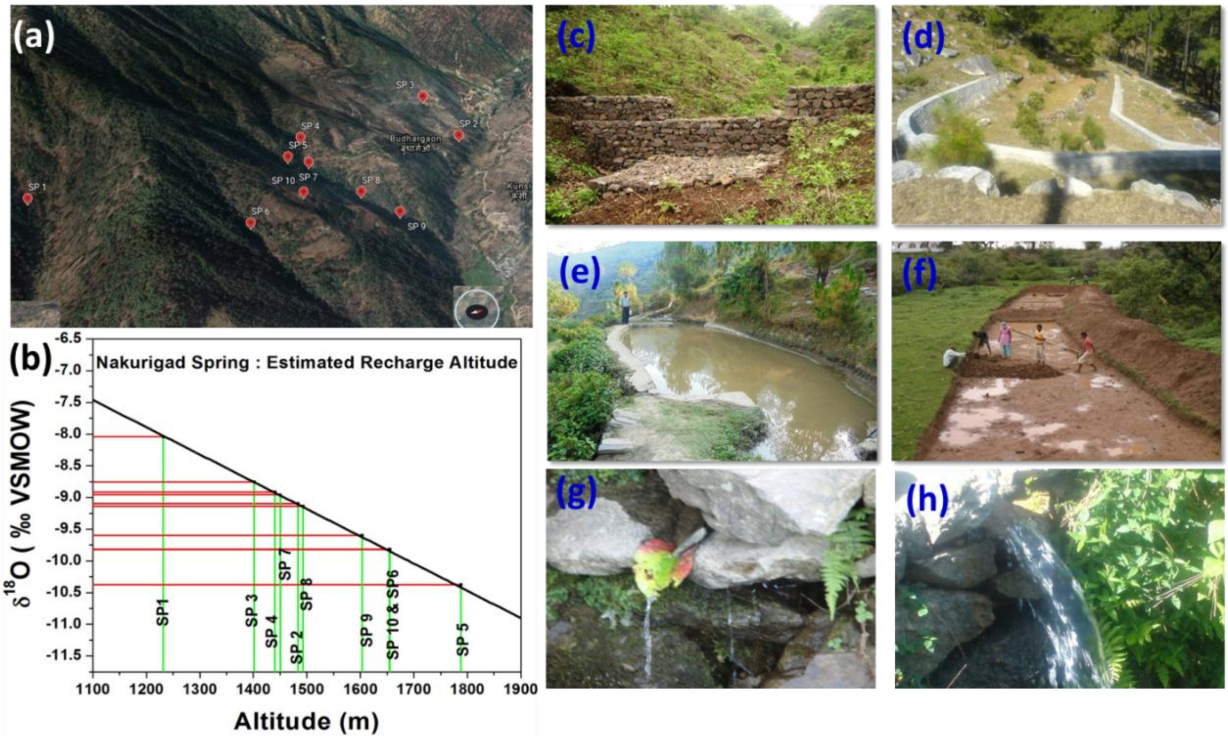

Figure 9. (a) Google earth map of spring sites, a typical site, b) recharge altitude of springs, c) gabion check dam, d) subsurface dykes, e) percolation pond, f) contour trenches and spring disharges g) before and i) after construction

7. Conclusion

Significant advances have been made through application of isotope techniques, which have provided better insights into factors and processes affecting surface water, groundwater and precipitation characteristics. Environmental stable isotopes (^{2}H, ^{18}O, ^{13}C, ^{15}N, ^{35}S etc.) find potential applications in understanding the groundwater source, interconnections and contaminant sources, whereas radioactive isotopes (^{3}H, ^{14}C, etc.) are being used to determine the groundwater 'ages' or 'travel times', which can infer the sustainability of water resources, transport as well as degradation rates of solutes. Injected isotopes are very handy for localized studies to determine the groundwater flow and velocity, estimation of recharge and migration of contaminants in saturated and unsaturated zones. Environmental isotopes in conjunction with modeling tools can provide precise and accurate information which can help the water managers and agencies to take up appropriate measures for designing effective water usage and management of water resources. Introduction of laser based isotope analysers, which can measure both ^{2}H and ^{18}O simultaenouly in a short time and low cost compared to mass spectrometers is going to widen the user base in both research as well as academic institutions and further propagate of this technlogy. Advances in isotope measurement systems and applications are going to pave a way for a wider and regular use of isotope technology in future.

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Chapter 3: Radiation technology for sustainable waste management: A brief overview

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Abstract: *The use of ionizing radiation, such as gamma rays, electron beams, X-rays, etc., for developing novel materials and methodologies is a sustainable, environment-friendly and efficient approach towards tackling many environmental pollutants of critical concern to human health and the ecosystem. Functional materials based on radiation grafted polymers, crosslinked gels, polymer composites, etc., have been explored for their ability to sequester toxic water pollutants, such as textile dyes, metal ions, etc. from water bodies. Radiation-assisted pollutant degradation and the utilization of ionizing radiation in developing robust catalytic systems for pollutant remediation have been investigated. Similarly, radiation hygienization of sewage sludge have also garnered sizeable attention over the years in the relentless efforts towards developing waste to wealth-based management strategy, wherein infectious sewage sludge was converted into enriched manure for land application. This chapter recapitulates the sundry applications where radiation technology has proved its worth in offering novel waste management solutions to many of our concerns pertaining to environmental pollution remediation. In line with the United Nation's sustainable development goals (SDGs), radiation technology offers a holistic and safe management process for providing a cleaner and healthier environment.*

1. Introduction

Population growth and rapid industrialization at an unprecedented scale has taken a heavy toll on our land, water, air and other natural resources over the years. Copious amounts of domestic and industrial waste are generated on a daily basis, which has resulted in our water bodies being infested with pollutants, such as disease-causing pathogenic microorganisms, dyes, heavy metal ions, pharmaceutical compounds, and other undesirable noxious chemical compounds in varying compositions [1]. At the same time, indiscriminate dumping of solid waste has also impacted our soil quality, besides exposing the public to various pathogens, vectors and general discomfort. Especially in the context of a country like India, which is populated by over 1.4 billion and is a rapidly growing economy with almost 50 % of its population residing in urban areas, the need for efficient, affordable and low carbon footprint treatment methodologies for management of wastewater and associated wastes has become paramount.

The infiltration of water bodies by metal ions, can arise from both geogenic and anthropogenic sources. These pollutants, such as chromium, arsenic, cadmium, lead, mercury, uranium, etc., are notorious for their chemotoxicity and adverse effects on biological pathways. The toxic heavy metals have been identified to inflict both acute and chronic toxicity on various organs like kidneys, lungs, nervous system and even the reproductive system [2]. Similarly, colored wastewater generated from industries like textile, paper, leather tanning, cosmetics, printing and dye manufacturing units, is not only an aesthetic pollutant, but it also contaminates ground water and sabotages aquatic ecosystems by modifying the aquatic environment, both physically and chemically [1]. The intense color of dyes reduces transmission of sunlight into water and decreases the dissolved oxygen content by impairing the photosynthesis activity of aquatic plants and algae, depreciating their proliferation and affecting other aquatic life forms as well. Another important class of pollutants, termed 'contaminants of emerging concern' (CECs), includes pollutants, such as pharmaceuticals, personal care products, endocrine-disrupting compounds, microplastics, etc. The CECs are synthetic or naturally occurring chemicals that are increasingly detected in the environment but are not yet regulated. Traditional wastewater treatment plants are not capable of fully removing CECs, leading to their continuous accumulation in the environment [3].

Sewage is another category of wastewater which originates exclusively from human activities and typically contains less than 0.1% solid consisting of organic and inorganic matter. Throughout its journey from collection points to sewage treatment plants (STP), it gets further contaminated by chemicals, pharmaceuticals, insecticides, pesticides, heavy metals, etc., entering through different sources. India is the most populated country in the world with a population of around 1.4 billion and produces about 1,11,972 million litres per day (MLD) of wastewater, of which urban India generates 72,368 MLD of wastewater [4]. Thus, disposal of huge quantity of municipal sewage sludge generated in sewage treatment plants, is becoming a serious problem for urban authorities, compounded by the lack of adequate space and adverse health effects on the populace.

With government agencies and regulatory bodies resorting to stricter discharge norms, the concepts of sustainable waste management as well as implementation of new technologies for water remediation, waste recycling and establishing a circular economy have taken centerstage. In the process, radiation technology has emerged as a dominant player in developing ionizing radiation based novel technologies and methodologies for addressing the numerous concerns that plague our environment.

2. Radiation processing: fundamental aspects

Radiation processing involves the use of ionizing radiation under a controlled environment to alter or modify the chemical, physical and biological properties of the irradiated materials, as per the target applications. ^{60}Co based gamma irradiator and electron beam accelerator are the most commonly used radiation sources for radiation processing applications. Briefly, when a molecule is exposed to high energy ionizing radiation, two primary processes occur simultaneously: i) Ionization and ii) Excitation. These primary processes lead to subsequent secondary processes, such as recombination, molecular dissociation, etc., giving rise to highly reactive species, e.g., free radicals and solvated ions. These reactive species act as precursors for subsequent chemical reaction in the materials, including oxidation, reduction, polymerization, crosslinking, degradation, etc., which lead to ~~the~~ desired modifications in the properties of the materials required for different applications.

In case of polymers, depending on the modifications required, four processes are primarily used: i) Radiation induced graft polymerization (RIGP), ii) Radiation induced curing, iii) Radiation induced degradation and iv) Radiation induced crosslinking (Figure 1). Radiation induced crosslinking and degradation are bulk modification processes, Radiation grafting and curing, on the other hand, are mainly surface modification approaches.

In RIGP, new polymer chains of desired functional monomers are grown over an existing polymer backbone using ionizing radiation as a source of initiation, which generates free radical sites on the existing polymer backbone. These free radicals initiate graft copolymerization chain reaction from the monomers, leading to the growth of functional grafted chains covalently anchored to the base polymer.

Radiolytic synthesis of metal nanoparticles is another important application of ionizing radiation, wherein the radiolytic reducing species formed from radiolysis of water initiate the formation of nanoparticles, thereby avoiding the addition of chemicals like reducing agents, solvents, etc., and offering an environment-friendly synthesis protocol.

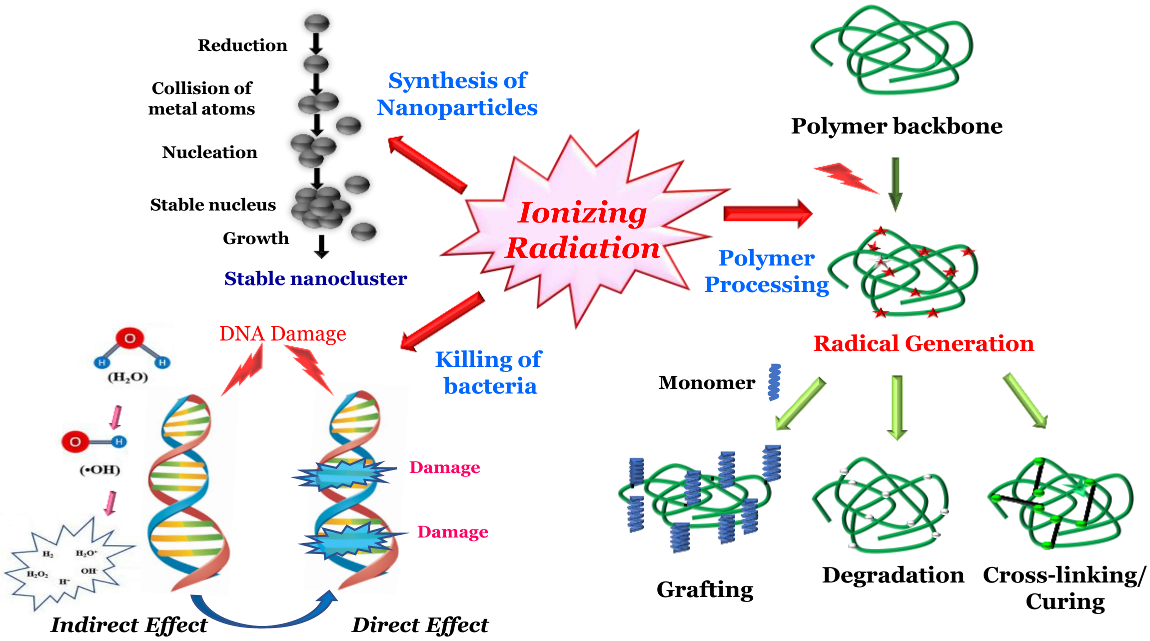

Figure 1. Ionising radiation-based processes used for different applications

The effect of ionizing radiation on living organisms, and microorganisms in particular, has been well established. Radiation targets the DNA of living organisms either directly or indirectly, as illustrated in Figure 1. In the direct mode, radiation damages the DNA through bond cleavage, modification, etc., while in the indirect mode of action, it first interacts with the water molecules present in the cell, forming radiolytic reactive species, ($OH^{\cdot}$, e_{eq}^{-} and $H^{\cdot}$). These species then attack and damage the DNA. Based on this process, a range of applications have been established at commercial scale, such as medical sterilization, blood irradiation, food irradiation, sewage sludge hygienization, etc.

3. Ionizing radiation for waste management

3.1. Radiation grafted Adsorbents for remediation of water pollutants

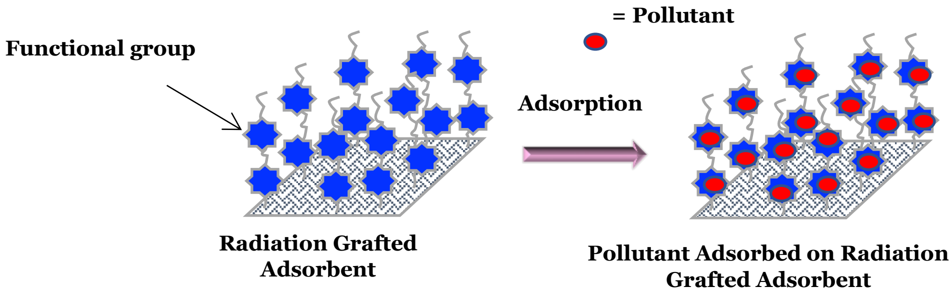

Figure 2. Schematic of pollutant adsorption on radiation grafted functional adsorbent

RIGP is an attractive proposition to develop functional adsorbents for the sequestration of various pollutants, such as dyes, heavy metal ions, etc., from contaminated water bodies (Figure 2).

While conventional wastewater remediation strategies, such as the use of co-precipitation, activated sludge treatment (biodegradation), ion-exchange resins, activated charcoal, reverse osmosis, membrane filtration, etc., suffer from limitations in some form or the other, adsorption process has been observed to be amongst the most practical methodologies, primarily because of advantages, such ease of preparation and operation, good affinity for pollutant due to presence of suitable functional groups, efficient, continuous flow mode operation, economic viability, up-scalability, etc.

3.1.1. Radiation assisted adsorbents for remediation of textile dyes

The textile industry is extremely water intensive and uses water for numerous treatments throughout the production process, such as sizing, de-sizing, scouring, bleaching, mercerizing, dying, printing and finishing. After dyeing and printing process, about 300,000 tons of unused dyes are reportedly discharged annually into effluent treatment plants (ETPs) worldwide [5]. ~~The~~ Treatment of the colored dye wastewater is of critical importance to ensure water reuse and to preserve our existing ground water resources. However, dye removal is complicated due to the fact that many of them are resistant to thermal/photo/bio-degradation ~~as~~ owing to their complex chemical structures. Besides, during anaerobic microbial degradation, some of the dyes can even lead to generation of carcinogens and mutagens as by-products [6].

The complexity of textile dye wastewater composition prevents deployment of a universal method for their treatment and therefore, combinations of different processes are being used to serve the purpose. The most popular combination method currently prevalent in the industry ~~is~~ involves coagulation and biodegradation, followed by filtration via reverse osmosis. But these methods are severely restricted in their utility for efficient, cost-effective decolouration and subsequent reuse of treated water. Nevertheless, the adsorption approach seems to be the most appropriate choice since it is not only comparatively simple and efficient, but also cost-effective. The different adsorbents reported in literature over the years include activated carbon, cellulose, chitosan, bio-composite adsorbents, etc. However, low-cost, high capacity, easily available, up-scalable and bio-degradable functional adsorbents are the need of the hour to make the process economically and environmentally sustainable at industrial scale treatment. In order to fabricate such functional adsorbents, RIGP process has been extensively used, which offers many advantages over conventional chemical functionalization processes, such as being a single step, room temperature and organic solvent free green synthetic route.

Several radiation-grafted adsorbent systems have been developed and demonstrated to be effective towards remediation of ionic dyes. For example, Kumar et al. [7] reported the use of (Vinylbenzyl)trimethylammonium chloride (VBT) as a grafted quaternary ammonium group containing monomer on a cellulose matrix for the uptake of anionic dyes, such as AB25, AB74 and AY99. Similarly, [2-(Methacryloyloxy)ethyl]trimethylammonium chloride (MAETC) grafted adsorbent for remediation of dyes AB25 and AB74 has also been reported [8]. These adsorbents have high uptake capacities in the range of 300-500 $mg.g^{-1}$. Additionally, the use of cotton cellulose fabric as the adsorbent matrix ensures biodegradability and ease of disposal. In an alternate strategy, the remediation of cationic dyes using anionic adsorbents has been explored. Recently, Misra et al. [9] have reported a viable radiation mediated approach, wherein VBSA (4-vinylbenzenesulfonic acid sodium salt) was grafted on to cotton cellulose fabric to develop an anionic grafted adsorbent for uptake of cationic dyes. Substrates, such as Teflon and Polyurethane Foam (PUF) [10, 11] have also been functionalized with acrylic acid (AA) for adsorption of basic dyes BR11 and BR29. Using polymers, generated as wastes during various industrial processes (cellulose fabric, Teflon scrap, PUF waste, etc.), as the adsorbent backbone, is an ingenious "waste to wealth" transformation strategy, whereby one waste form (polymer) is suitably modified and utilized to remediate another waste (i.e., textile effluent). A range of cationic and anionic adsorbents based on grafted cellulose can be developed using different functional monomers. Some of these grafted adsorbent systems developed in our group have been upscaled and successfully tested under relevant industrial environments. One such system, has been converted into a viable green technology (RAd-TED) for textile effluent treatment as a part of the Department of Atomic Energy (DAE), Government of India's societal initiative mandate. Based on the experience drawn from rigorous field trials, a 75 KLD industrial scale treatment plant has been conceptualized, designed and installed in one of the cotton printing and dyeing industries in Jodhpur, Rajasthan to treat the colored dye effluent and ensure reuse of the treated water within the industry (Figure 3). The technology has received "Consent to Establish" from Rajasthan State Pollution Control Board (RSPCB) and is available on BARC portal for Transfer of Technology (ToT) to interested licensees.

Figure 3. (a) 75 KLD plant installed at textile industry in Jodhpur, Rajasthan; (b) Images of dye effluent samples from cotton industry before and after treatment.

A host of other radiolytically engineered dye adsorbents have been prepared over the years and demonstrated at various scales for removal of ionic dyes. Singh et al. have provided a detailed review on the applications of grafted polysaccharide copolymers for remediation of textile effluent dyes [12]. Biopolymers, such as chitosan, CMC, starch composites, etc., have been grafted with various functional monomers (AA, acrylamide, polyacrylonitrile, polyanilines, etc.), and tested for dye uptake. A significant volume of work has also been reported on the functionalization of biomass (e.g., extracts from forest and agricultural wastes, such as rice husk, fruit peels, sugarcane bagasse, gums, etc.) to develop environment-friendly bio-adsorbents. Certain adsorbents involve a dual strategy of crosslinking and grafting to enhance the physio-chemical strength and improve the shelf lives. Elella et al. have reported the synthesis of crosslinked xanthan gum (XG) films grafted with poly (N-vinyl imidazole) and demonstrated their adsorptive capacity for crystal violet dye [13]. Some of these systems have the need to be upscaled for large scale commercial applications as greener, ecologically sustainable alternatives to conventional treatment approaches.

3.1.2. Adsorbents for remediation of toxic metal ions

RIGP has been demonstrated to be an effective process for synthesis of adsorbents with tunable selectivity towards various metal ions. The concept can be employed to target various metal ions, such as U, Cr, Cd, As, Pb, Hg, etc., that plague our water bodies. For example, amidoxime and phosphate groups have both been reported for their excellent ability to selectively bind to uranium ions. Working on this principle, radiation grafting techniques have been applied to incorporate the desired functional groups onto a stable polymer matrix. One of the reported systems for U remediation is an amidoxime grafted polypropylene (PP) matrix which was demonstrated to be highly effective towards U recovery from sea water [14]. The adsorbed uranyl ions could also be eluted with acid solutions and the adsorbent could be reused for multiple cycles. Co-grafting of the precursor acrylonitrile monomer with other monomers, such as methacrylic acid prior to amidoxime conversion has also been explored and demonstrated to be effective towards U uptake [15]. Das et al., have grafted monomer EGMP (Ethylene glycol methacrylate phosphate) onto PP for U recovery [16]. Rana et al. recently carried out a two-step synthesis of a U adsorbent via grafting of monomer GMA onto non-woven PE followed by conversion of the epoxide groups to sulfonic acid via sulfonation [17]. Recently, our group has developed a new system, wherein a phosphate group containing monomer B2MEP (Bis[2-(methacryloyloxy)ethyl] phosphate) was grafted onto cotton cellulose using gamma radiation induced RIGP (Figure 4) [18]. This B2MEP-g-cotton system (*CellUSorb*) has been demonstrated to show excellent U uptake capacity along with high selectivity and fast uptake kinetics. *CellUSorb* has also been tested using U contaminated ground water samples collected from affected areas and found to be successful in reducing the uranium concentration below WHO permissible limits (30 ppb).

Arsenic (As) in drinking water is a critical environmental hazard in several parts of India. The World Health Organization (WHO) and the U.S. Environmental Protection Agency (USEPA) have recommended the As Maximum Contaminant Level (MCL) for public drinking water supplies to be less than 0.010 mg/L (10 ppb). As per WHO estimates, around 220 million people worldwide are at risk of being exposed to As contaminated drinking water. To provide a viable solution to this problem, a cotton cellulose-based adsorbent (PMAETC-*g*-cellulose) developed by RIGP, was successfully employed [19].

Cr and Cd are two other toxic metal ions that have been a cause of major concern worldwide. Cr waste is generated in large amounts from electroplating, leather tanning, and textile industries. To mitigate this problem, radiation grafted adsorbents based on functional moieties, such as amidoxime, diamines and MAETC have been reported for meeting the WHO permissible Cr limits of 50 ppb in drinking water [20, 21]. Cd pollution arises from burning of fossil fuels, incineration of municipal waste, nickel-cadmium batteries, scallop processing industry, etc. An iminodiacetic acid type adsorbent (IDA-ad), prepared via RIGP was reported to selectively remove Cd from water. Furthermore, the collected cadmium could be eluted by acid solution and used as a metal resource [22].

Similarly, different types of adsorbents have been fabricated to remove metal ions, such as Cu, Ni, Co, Pb, Au, etc. Nasef et al. have utilized the gamma radiation induced grafting techniques to develop sulfonate functionalized polyethylene-based adsorbents for a range of metal ions that follow the adsorption efficiency order of Ni(II)>Co(II)>Cu(II)>Pb(II)>Ag(I) [23]. Kumar et al. [24] have also discussed the feasibility of using AMO-g-PP adsorbents for the sequestration of multiple heavy metal ions such as Co^{2+}, Ni^{2+}, Mn^{2+}, and Cd^{2+}. In their recent review on wastewater treatment methodologies based on radiation technology, Torkaman et al. [25] have discussed the importance of RIGP in developing adsorbents for metal ions and the challenges involved in their optimization and potential industrial applications, with a special emphasis on the removal of heavy metals. Of late, our group has also successfully tested the efficacy of a sulphonic acid functionalized biodegradable adsorbent, prepared via RIGP of monomer styrene sulphonate sodium salt onto a cellulose backbone, for recovery of heavy metals, such as Pb^{2+}, Cd^{2+} and Ni^{2+} from water.

The presence of Mercury (Hg(II)) in water bodies poses a pressing threat not only to aquatic life forms, but also to human health. It is well known for its high neuro- and reproductive toxicities and long-distance transportability. To mitigate this problem, a novel thiol (-SH), amine (-NH-) and carboxylic (-COOH) group containing biodegradable adsorbent was fabricated via radiation mediated engineering for selective remediation of Hg(II) in water, with an adsorption capacity of over 175 $mg.g^{-1}$ and fast uptake kinetics (Figure 4). Moreover, the adsorbent could be regenerated and reused for >5 iterative cycles using an optimized eluent system [26].

Many of the adsorbent fabrication protocols employ a secondary chemical modification step wherein grafted moieties are chemically converted into the desired functionalities. Figure 3 illustrates a flowchart for two step preparation of metal ion adsorbents through RIGP and chemical modification process. Using this approach, Ueki et al. [27] have recently reported a new functional group, viz. Piperazinyl-dithiocarbamate which was incorporated onto fibrous polymeric membranes via a modified emulsion based RIGP process. These adsorbents have been observed to possess high uptake capacities, while some can selectively adsorb heavy metal ions over light metal ions, following an adsorption trend $Na^{+} < Mg^{2+}, Ca^{2+}, Co^{2+}, Cd^{2+} < Pb^{2+} \ll Cu^{2+}$, and $Co^{2+} \approx Ni^{2+} < Zn^{2+} \ll Cu^{2+}$.

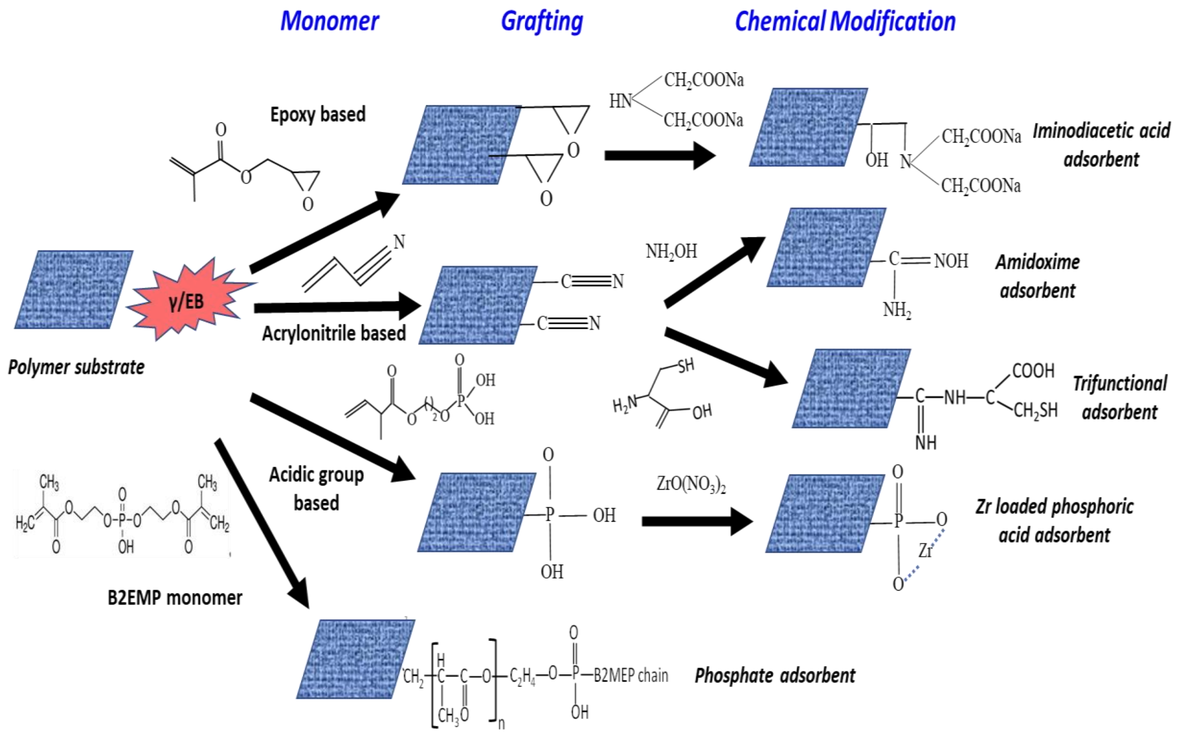

Figure 4. Schematic of two step synthesis of adsorbent: RIGP of polymer substrates followed by chemical modification

3.2. Degradation and reduction-based remediation of water pollutants

The use of ionizing radiation has been reported for degradation and reduction-based remediation of number of pollutants including toxic metal ions, dyes, pharmaceuticals, pesticides, persistent organic pollutants (POPs), etc. In this regard, ionizing radiation, mainly gamma and electron beam (EB), has been employed either directly for degrading pollutants or indirectly by employing radiation for fabrication of efficient catalytic systems, which have been studied for catalytic remediation of pollutants.

3.2.1. Radiation assisted degradation of water pollutants

Various methods have been studied for the degradation of pollutants in water, including photocatalysis, advanced oxidation processes (AOPs), ozonation, and biological treatment. The use of photocatalysts, such as TiO_2, involves generation of $OH^\bullet$ that degrade organic pollutants under UV light, but suffers from limitations, such as low efficiency under visible light, slow degradation rates and catalyst deactivation. Another approach based on oxidative degradation of pollutants is ozonation. However, requirement of constant ozone supply makes it expensive due to high energy consumption during ozone production, while limited solubility of ozone in water further restricts its efficiency. Fenton reactions, though efficient in producing radicals, are constrained by strict pH requirements, sludge generation, and the need for additional reagents, making large-scale implementation costly and environmentally burdensome. Other AOPs, such as UV/H_2O_2 and persulfate-based oxidation, often suffer from limitations like high reagent costs and secondary pollutant formation, etc. Biological treatments/Bio-degradation, while eco-friendly, are ineffective for highly recalcitrant pollutants, such as synthetic dyes, pharmaceutical residues, endocrine disruptors, and per- and polyfluoroalkyl substances (PFAS) [28]. In contrast, gamma and EB irradiation offer some advantages due to their ability to simultaneously induce oxidation and reduction reactions, without the need for additional chemical reagents. These ionizing radiation methods generate $OH^\bullet$radicals and hydrated electrons, allowing for the breakdown of recalcitrant pollutants [28]. Thus, while AOPs face challenges in cost, by-product formation, and scalability, ionizing radiation techniques may provide a more sustainable solution for water purification through better degradation efficiency, operation in ambient environment and eliminating the need for additional chemicals that can cause secondary pollution.

3.2.1.1. Mechanism of Ionizing Radiation in Water Treatment

Ionizing radiation degrades pollutants through water radiolysis, generating reactive species ($OH^\bullet$, e_{eq}^-, $H^\bullet$) that play crucial roles in oxidation and reduction processes and facilitate the breakdown of contaminants. $OH^\bullet$ is a strong oxidizing species that can break down organic pollutants by various mechanisms, such as H abstraction, addition to double bond, etc., while e_{eq}^- acts as a strong reducing agent, aiding in the degradation of halogenated compounds, nitrates, and heavy metals. This mechanism is particularly effective for detoxifying POPs, such as pesticides, dioxins, polychlorinated biphenyls (PCBs), etc. [28]. $H^\bullet$ also acts as a reducing agent albeit less potent than e_{eq}^- and acts by undergoing reactions, such as H abstraction, addition to double bond, etc., wherein hydrogenation, alters the structure of pollutants, making them more biodegradable. Overall, these reactive species interact with pollutants, leading to cleavage of molecular bonds, ring-opening reactions, etc. [29].

3.2.1.2. Gamma and EB Irradiation for degradation of water pollutants

Studies have demonstrated effectiveness of ionizing radiation in degrading pesticides, pharmaceuticals, POPs, cyanotoxins, PFAS, etc. For example, Li et al., have reported degradation of Deoxynivalenol (DON), a mycotoxin commonly found in grains and agricultural runoff [30]. Another reported work describes application of gamma irradiation in the treatment of water sources contaminated with cyanotoxins, such as Microcystin-LR (MC-LR), a potent hepatotoxin produced by harmful algal blooms. Gamma irradiation was reported to be highly effective at degrading MC-LR, while simultaneously inactivating the cyanobacteria responsible for its production, making it a dual-purpose solution for treating algal bloom contamination in freshwater systems [31].

Radiation assisted degradation of pharmaceuticals, such as of ibuprofen, carbamazepine, ciprofloxacin and tetracycline [28, 29] have been reported. Studies have demonstrated that gamma irradiation is particularly well-suited for treating large-scale wastewater systems where conventional methods fail, such as hospital effluent containing a mix of pharmaceuticals, disinfectants, and antibiotic-resistant bacteria [31].

EB has demonstrated significant potential in the treatment of PFAS, commonly known as "forever chemicals." PFAS are notorious for their environmental persistence and resistance to degradation by conventional treatment methods. Recent studies have shown that EB irradiation, particularly at doses between 10 and 30 kGy, can achieve partial to near-complete defluorination of PFAS compounds, effectively breaking down these highly stable molecules [29]. Another study on textile wastewater treatment showed that EB irradiation at 5–15 kGy removed more than 85 % of synthetic dyes and surfactants, significantly improving water quality and reducing aquatic toxicity [32]. Research on continuous-flow EB reactors has demonstrated that the hydrodynamic behaviour of these reactors significantly influences pollutant degradation rates. A study by Rui et al. emphasized the importance of computational fluid dynamics (CFD) simulations for optimizing EB reactor design, ensuring even dose distribution and maximizing degradation efficiency [33]. These findings highlight the importance of process engineering in scaling up EB technology for industrial wastewater treatment applications.

One major limitation of gamma radiation assisted degradation of pollutants is the high capital cost and regulatory constraints associated with handling radioactive materials, such as ^{60}Co, which is commonly used as a gamma source. On the other hand, unlike gamma irradiation, EB treatment does not require radioactive isotopes, making it a safer and more scalable solution for industrial and municipal applications. However, for applications where deep penetration and high-energy radiation are required, gamma irradiation remains one of the most effective methods for degrading highly recalcitrant pollutants. Critical parameters that influence the efficiency of gamma and EB irradiation in water treatment are the absorbed dose and treatment time. Higher doses generally result in greater degradation efficiencies, but optimizing the process for specific pollutants is essential to minimize energy consumption and operational costs, especially in case of EB. Additionally, ionizing radiation can simultaneously degrade multiple contaminants, including pathogens, ensuring a broader spectrum of water purification.

While gamma and EB irradiation has demonstrated significant advantages in pollutant degradation, the integration of EB with other advanced treatment processes presents new opportunities for optimizing efficiency and cost-effectiveness. Recent research has explored the synergistic effects of EB irradiation with adsorption, photocatalysis, and membrane filtration, aiming to enhance degradation rates, while reducing energy consumption. A study by Getoff highlighted the potential for combining EB irradiation with TiO_2 photocatalysis to accelerate the breakdown of persistent organic pollutants, achieving higher mineralization rates compared to standalone processes [34]. Additionally, low-energy EB reactors have been developed to achieve high degradation efficiencies, while reducing operational costs, making EB treatment more economically viable for large-scale applications [32]. As research continues, efforts to optimize dose distribution, reactor design, and to develop hybrid treatment approaches will play a crucial role in mainstreaming EB technology as a key solution for sustainable water management, while in case of gamma, cost reduction strategies, public awareness and regulatory adaptations will be essential for its widespread adoption in municipal and industrial wastewater treatment.

3.2.2. Radiation assisted fabrication of catalytic systems for degradation of water pollutants

Another important approach based on ionizing radiation for degradation of water pollutants includes fabrication of catalytic systems, including nanoparticles (NPs) and enzymes based catalytic systems, for degradation of water pollutants. These catalysts facilitate oxidative and reductive degradation pathways, making them highly effective in breaking down recalcitrant compounds. In this regard, radiation provides an efficient tool to fabricate suitable functionalized support for anchoring catalytically active species using green fabrication methodology like RIGP. Additionally, radiation in many cases have also been used for synthesis of NPs, wherein external reducing agents are not required, thus providing green and eco-friendly fabrication routes and reducing the need for toxic chemicals in catalyst preparation.

Misra et al. have reported a green fabrication approach involving plasma and gamma radiation mediated fabrication of Pd NPs based catalytic system, wherein in the substrate was functionalized with plasma while Pd NPs were synthesized and simultaneously anchored on the functionalized polymer substrate. The catalytic system was demonstrated for catalytic reduction of carcinogen Cr(VI) to less toxic form of Cr(III) in batch as well as column mode with an conversion efficiency of >99.7 %. The catalytic system exhibited excellent reusability (~ 20 cycles) and storage stability (> 30 days) with minimal activity loss (~11%) [35]. In another study, Rawat et al. reported a highly efficient and reusable Au NPs based catalytic system for degradation of nitro pollutants and dyes [36]. These catalytic systems have also been investigated for catalytic degradation of pollutants in continuous flow operation, demonstrating their potential for practical viability.

Several different types of nanoparticles have been synthesized using radiation [37], with the efficiency of NPs based systems and nanocomposites for degradation of organic pollutants being extensively studied. For example, Zhao et al. reported γ-ray induced formation of oxygen vacancies and Ti^{3+} defects in anatase TiO_2 NPs that significantly enhanced their efficiency towards photocatalytic degradation of phenol [38]. In another work, Elbarbary et al. reported magnetically retrievable catalyst based on Fe_3O_4/polyvinylpyrrolidone (PVP) /polystyrene (PS) nanocomposite for catalytic oxidation of dyes, wherein gamma radiation induced polymerization was used to fabricate PVP/PS sphere [39]. In conclusion, radiation-assisted synthesis of NPs-based catalysts presents a highly efficient, scalable, and eco-friendly approach for water treatment applications. The ability to precisely control nanoparticle size, surface properties, and composition through gamma and EB irradiation enhances catalytic activity, stability, and pollutant degradation efficiency. Future research should focus on developing hybrid radiation-assisted catalytic systems, optimizing energy inputs, and integrating nano-catalysts with membrane filtration and biological treatment methods to create sustainable and cost-effective water purification technologies.

Radiation-assisted enzyme-based catalytic systems have also been developed for water pollutant degradation. Enzymes, such as oxidoreductases, laccases, and peroxidases, are widely used for the biodegradation of hazardous organic pollutants, including pharmaceuticals, phenols, and industrial dyes. However, challenges, such as enzyme deactivation, leaching, and low stability under extreme water treatment conditions have limited their large-scale application. RIGP provide a powerful tool for fabrication of functionalized supports to immobilize enzymes. Misra et al. have fabricated laccase enzyme based catalytic system, wherein the epoxy functionalized polyethersulfone (PES) support matrix was synthesized via RIGP, followed by covalent immobilization of laccase: the system was studied for degradation of textile dyes [40]. In another work, Kumar et al. developed a Horseradish peroxidise (HRP) enzyme based catalytic system by anchoring HRP on radiation functionalized polymer support for dye degradation [41]. One report also describes enhanced production (2-fold) of laccase enzyme upon irradiating endophytic fungus to 1.2 kGy, which in turn increased the dye degradation efficiency [42]. In addition to green fabrication of enzyme-based catalytic systems using radiation, future research should also explore hybrid approaches that combine enzyme catalysis with nanoparticle-enhanced oxidation and filtration technologies, with focus on scale-up feasibility for integrating these systems into large-scale wastewater treatment operations.

3.3. Ionizing Radiation for sewage sludge management

With the ever-increasing population and associated anthropogenic activities, water consumption and subsequent generation of wastewater (domestic sewage) has grown exponentially. A huge quantity of infectious municipal sewage sludge is being generated during the treatment of sewage in STPs. The present sludge disposal methods include disposal into sea (site specific), incineration (energy intensive) and land filling, which involves transporting the sludge to the far away dumping sites, leading to extra transportation cost. Additionally, the unregulated agricultural use of untreated sewage sludge can result in spread of diseases and ground water contamination.

On the brighter side, sewage sludge is a rich source of carbon and plant nutrients and can be used as an organic soil conditioner and manure after proper treatment. On an average, sewage sludge contains about 3-5 % nitrogen (N), 1-3 % phosphorus (P), and ≤1 % potassium (K). It can be applied to agricultural land (pastures and cropland), disturbed areas (mined lands, construction sites, etc.), plant nurseries, forests, recreational areas (parks, golf courses, etc.), cemeteries, highway and airport runway medians, and home lawns and gardens. The USEPA, the primary federal agency responsible for sewage sludge management, encourages the beneficial use of sewage sludge through land application, after it has been appropriately treated for its intended use. There are three primary factors that determine the quality of sewage sludge: (a) Presence of pathogenic microorganisms (Bacteria, Enteric virus, viable Helminth ova, etc.) (b) Presence of metal ions (As, Cd, Cr, Cu, Pd, Hg, Mo, Ni, Se, Zn.) and (c) Vector Attraction in Sewage Sludge (Rodents, flies, mosquitoes, birds, etc.).

Under the same regulatory norms, sewage sludge has been categorized depending on its pathogenic load. If pathogens (Salmonella sp. bacteria, enteric viruses, and viable helminth ova) are below detectable levels, the biosolids meet the Class A designation and there are no restrictions upon their land use. Class B sludge has pathogens in detectable level but these have been reduced to levels that do not pose a threat to public health and the environment as long as actions are taken to prevent exposure to the biosolids after their use or disposal.

Heavy metals can infiltrate domestic sewage through mixing of sewage water with industrial wastewater. In order to address this issue, the USEPA has proposed maximum acceptable concentrations of heavy metals in sewage sludge as per 40 CFR Part 503 regulations, based on the risk assessment studies (USEPA 1993) [43]. In the EU, these have been issued by the Directive 86/278/EEC of the European Commission (Commission of the European Communities 1986) [44]. Sludge with metal ion concentrations that exceed these limits are not considered fit for land application or soil amendment, whereas it is deemed “clean” if all the metal ion concentrations are within the prescribed ceiling limits. It must be noted that radiation treatment itself plays no role in changing the concentration of heavy metals in treated sewage sludge. Therefore, it is imperative to identify and contain the sources to keep the contamination levels within the prescribed limits. Irradiation of sludge neither affects the sludge organic C or N mineralization nor does it enhance the chemical extractability of nutrients or heavy metals.

Insects, rodents, birds and even domestic animals can transfer pathogens from sewage sludge to humans. These are termed as vectors that are attracted towards sewage sludge as a food source. Therefore, as per Part 503 regulations, it is important to reduce attraction of vectors to sewage sludge in order to prevent the spread of pathogens. Broadly speaking, the two primary routes by which this can be achieved are (a) by treating the sewage sludge to an extent that vectors will no longer be attracted towards it and (b) by placing a physical barrier between the vectors and sewage sludge. Category (a) can be further categorized into the following two options: (i) Biological processes that break down volatile solids and thereby, reduce available nutrients that can sustain microbial activities and lead to odour generation and (ii) Chemical or physical processes which retard or eliminate microbial activity.

3.3.1. Role of ionizing radiation

Ionizing radiation has been studied as an efficient sewage sludge hygienization process and successfully implemented for large-scale treatments [45]. Several studies have confirmed the efficacy of ionizing radiation in treating sewage sludge. Among the various types of radiation, such as gamma, beta, alpha, x-ray and UV, gamma radiation is the most commonly used for this application and is extensively documented [45]. It is an effective approach to minimize the pathogenic load in sewage sludge and make it safe for agricultural use. Irradiation destroys living organisms majorly by damaging its DNA. Besides, it can also lead to oxidation and degradation of organic molecules. It has been reported that ionizing radiation leads to significant degradation in the organic pollutants, such as polyaromatic hydrocarbons present in sewage sludge; with approximately 63 % degradation being observed at 10 kGy radiation doses in case of dry sludge [46].

As per USEPA-40 CFR Part 503, both gamma and beta rays (EB accelerated) are capable of destroying pathogens; though the efficacy of electron beam is dependent on its energy and penetration power. Ideally, an absorbed dose of 10 kGy or more is sufficient to reduce pathogenic viruses, bacteria, and helminths ova to below detection limits. Gamma rays from isotopes, such as ^{60}Co and ^{137}Cs are preferred over EBs because they possess substantial penetration thicknesses and are easier to process the dense sludge with better reliability. Ionizing radiation exposure has the potential to not only eliminate pathogens but also reduce smell, thereby contributing to vector attraction reduction, and degrade other unwanted constituents like weeds, chemicals, etc., to make the sludge safer for use.

3.3.2. State of the art

Radiation technology has been globally established at a commercial scale for sterilization of medical products, food safety and food preservation. Following this concept, the first ^{60}Co based sludge hygienization demonstration facility in India was set up at Vadodara, Gujarat in 1992 to hygienize liquid sewage sludge (with ~4-5% solid content). Code-named SHRI facility (Sludge Hygienization Research Irradiator), this concept plant demonstrated that 3 kGy of radiation dose was sufficient to deactivate ~99.99% of pathogenic bacteria in liquid sludge. The radiation processed sludge can be effectively utilized in improving crop yields. With over two decades of experience gained in running this plant, it has been observed and evaluated that radiation technology for dry sludge hygienization is relatively more economical, reliable and scalable to large scale application specially for cities with large populations. The dry sludge irradiation plant can be integrated with an existing STP or set up as a centralized facility catering to a number of STPs in the region. An average radiation dose of ~10 kGy is sufficient to hygienize dry sludge. This dose is administered as per the USEPA recommendation for Class A category bio-solids.

The gamma radiation hygienized sludge has been found to be a good growth medium for beneficial bacteria. The reduction in pathogen population in radiation treated sludge results in lower microbial competition for sludge nutrients. This enables more growth of inoculated beneficial microorganisms (Phosphate solubilizing, Rhizobium and Azotobacter) in the sludge converting it into a prospective bio-fertilizer. Use of such sludge therefore enhance the availability of N, P and K in soil. Treated sewage biosolids also improve soil physical and chemical properties, such as organic matter, water holding capacity, nutrients, pH balance, trace elements, stability and workability. Through better water retention and aeration, they stimulate biological activities in the form of increased root growth, worm and micro-organism populations, leading to an overall improvement in soil quality and agricultural yields [47].

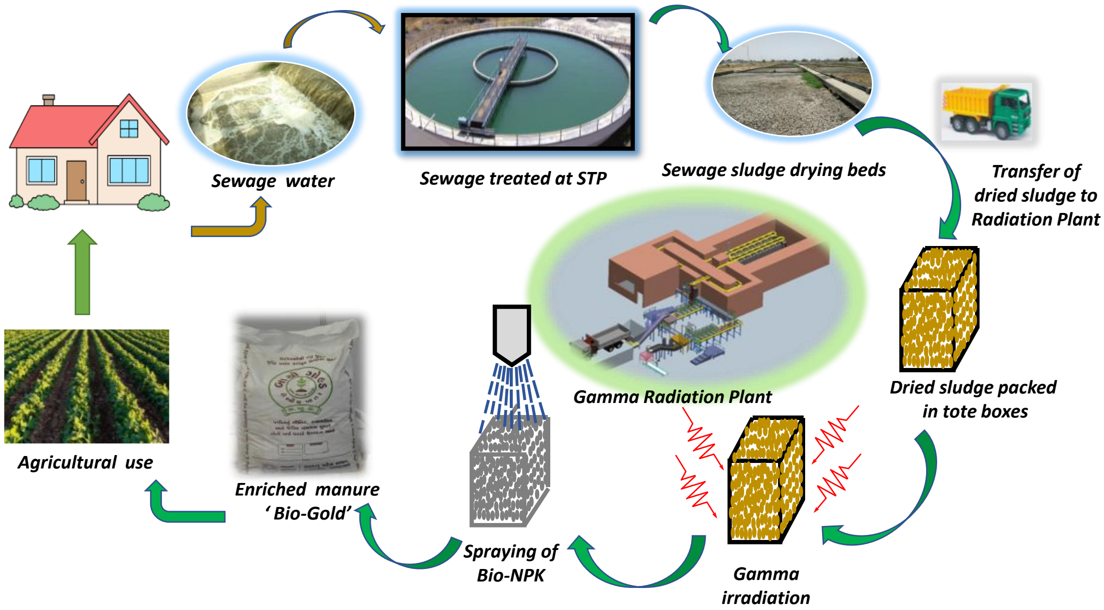

Figure 5. Process flow sheet depicting generation, treatment and conversion of sewage sludge to enriched manure for agricultural use via radiation treatment.

After successful validation of the process, on 21st April 2015, Ahmedabad Municipal Corporation (AMC) signed an MoU with Bhabha Atomic Research Centre, Department of Atomic Energy, Government of India, to set up a dry sludge hygienization facility with treatment capacity of 100 tons/day in Ahmedabad, globally a first of its kind. The facility commissioned and inaugurated on 2nd March 2019. A second plant on similar lines was commissioned at Indore, in collaboration with Indore Municipal Corporation.

As illustrated in the schematics of a typical radiation hygienization process (Figure 5), dry sludge containing 75-80% solid is initially transported to the irradiation facility and poured into crushers. The crushed sludge is transferred by a conveyor belt to be filled in aluminium tote boxes, which are then irradiated to an average dose of 10 kGy. The powdered, irradiated sludge is inoculated and enriched with useful bacteria using an automated spray unit containing the liquid bio-fertilizer. The hygienized, enriched sludge is subsequently filled in bags at the bagging station and sealed for distribution. For quality assurance, batch wise measurement of microbiological population and heavy metal concentration in the sludge samples before and after irradiation are routinely recorded.

4. Conclusion and way forward

Radiation technology is increasingly being employed to develop and upscale new methodologies for wastewater remediation through use of grafted/functionalized biodegradable adsorbents, radiation fabricated catalytic systems, and through direct degradation of pollutants using radiation. Government agencies and R&D institutes working on such technologies need to work in tandem and pursue an aggressive policy to facilitate smooth transition of radiation-based applications from the lab to the land. This would not only negate the general stigma associated with the use of radiation, even in the case of societal applications, but would also help launch a range of green, environment friendly technologies that can replace conventional remediation strategies. Simultaneously, a global thrust is also required to diversify and expand radiation technology applications into the arena of emerging pollutants, such as pharmaceutical waste, fertilizers, E-waste, etc., so as to address the concern of environmental pollution in a more holistic manner. A greater emphasis needs to be placed on technologies advocating circular economy and those that seek to realize the UN's Sustainable Development Goals (SDGs).

Similarly, value added products/formulations can be developed using hygienized sludge along with useful bacteria, sea weeds and other wastes (organic and inorganic). Despite not being a lucrative business model, radiation-based sludge hygienization plants can be set up by municipal corporations and run with marginal profit with the primary goal of benefiting the masses by safeguarding the environment and overall societal health. India has an ambitious nuclear power program and as a result the availability of ^{60}Co is assured for many years through Board of Radiation and Isotope Technology (BRIT). The ongoing indigenous EB accelerator program of DAE would also be able to supplement the increased demands for such applications in future. With the Government of India's new focus on development of technologies for Swachh and Swasthh Bharat, radiation technology is a promising technology which can contribute gainfully to achieve this objective and promote overall welfare.

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Chapter 4: Food Irradiation Technology: Potential Role in Agro-Economical Sustainability

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Abstract: *Food and Agriculture Organization (FAO), United Nations has estimated the annual loss and wastage of food up to 33% worldwide, costing severely to economy, environment, and society (Geraldine et al., 2017). Reduction in global food losses by 50% till 2030 has been fixed as a part of Sustainable Development Goal (SDG) by the United Nations. Food ecosystems having huge losses also lead to unsustainable levels of pollution and waste threatening human health and the environment. Therefore, addressing food loss and waste is very important to improve food and nutrition security, as well as to meet climate goals and reduce stress on the environment. Production of food is also very much resource intensive. It primarily involves global land (total 20%), water withdrawals (70%), and energy consumption (32%) and that at the cost of solid waste generation and emissions of greenhouse gas (GHG) and some other pollutants. Food Loss and Waste accounts for global Greenhouse Gases (GHG) emissions to the extent of 8%.*

Besides, foods often get contaminated with unwanted physical, chemical or biological entities. Physical contaminants could be dirt, pests, hair, fingernails, glass, and metal. Chemicals contaminations happen due to pesticides, herbicides, veterinary drugs, natural toxins, food adulterants, and polluted environmental components such as water, air or soil. Biological contaminates includes bacteria, fungi, viruses, and parasites. Besides food could also get contaminated with pathogens and work as a carrier to transmit it to a healthy individual causing illness and in rare cases even death (WHO, 2010).

To address these concerns, there is an utmost need to deploy the technology having broad spectrum applications while retaining the wholesomeness of the produce. Radiation processing of food is one such technology. This technology could be considered as more than 100 years. In 1905 patents were granted for the claim that ionizing radiation has ability to kill bacteria in foods in the USA and Great Britain. Further in 1920 Otto Wust, a German Scientist filed a patent from the French Government for his innovation that ionizing radiation could preserve food. At the same time period efficacy of X-Rays in eliminating Trichina spp from food was also reported. In 1958, the first commercial food irradiation facility started in Germany where spices, tubers, onions, frog legs and seafood were irradiated and sold at retail market.

1. Radiation processing of food

In this process food commodities and agricultural produce are exposed to controlled amount of radiation energy from approved radiation sources as detailed further. Benefits of the treatment includes inhibition of sprouting in onion and potato; ripening delay in certain fruits like mango and banana; disinfestation of insect pests from grains (cereals and pulses) as well as spices; killing of parasites and microorganisms from various foods and phytosanitary treatment of fruits and vegetables to overcome quarantine barrier of trade (Codex, 2003; Diehl, 1995, 2002; FAO/IAEA/WHO, 1999; Farkas, 2006)).

Radiation sources as approved by International Atomic Energy Agency (IAEA), an International statutory organization dealing with nuclear technologies are as follows:

i. Gamma radiation emitted by Cobalt-60 radioisotope (Energy 1.17 and 1.33 MeV)
ii. Gamma radiation emitted by Cesium-137 radioisotope (Energy 0.66 MeV)
iii. X-rays (Energies not exceeding 7.5 M eV), and
iv. E beam (Energies not exceeding 10 MeV): For e-beam energy of 7.5 MeV or less to convert into X-ray the recommended target should be either gold or tantalum. For e-beam energy of 5.0 MeV or less to convert into X-ray the target should be either tungsten, gold or tantalum. In case of E beam, measurable beam energy parameter is the most probable energy (Ep).

Primary high-energy electrons from E-beam lead to generation of secondary electrons. Similarly, in case of Co-60 or Cs-137 radioisotopes, photons from radioactivity decay or bremsstrahlung X-rays produce secondary electrons. These electrons interact with food matter through various processes. In case of food, it is primarily Compton scattering. Electrons, having energy of 10 MeV, have penetrating capacity of approximately 5-cm in the food product with density quite close to aqueous system. On the other hand, photons being an uncharged particle exhibit comparatively very higher level of penetration. The required penetration range in the container is determined by the dimensions and mass of the product. Electron beam of energy 10-MeV can treat the product having 1.0 g/cm^3 density up to 8 cm and of 0.2 g/cm^3 density up to 40 cm when the product is irradiated from both the sides. The limited penetration of electron beams restricts their use to treating the surface of foods, thin packages or a shallow stream of grains, powders, or liquids. E-beam dose rate can be achieved as per the requirement by adjusting the primary electron beam current. For the products having larger volumes and higher densities photon energy from Co-60 decay or X-rays (bremsstrahlung) are preferred. Irrespective of the said limitations, all these three types of radiation have similar mechanism of molecular interactions.

2. Typical components of a Food Irradiation Facility

Radiation sources as described above, irradiation cell (1.5 - 2.0 m thick in case of gamma facility) as a biological shield and a system to move the product (conveyor) are the important components of a food irradiation facility. Irradiation cell is made of concrete cement of high density (2.5 g/cc) to avoid any escape of radiation outside the cell and thus ensuring safety of facility operators. In case of E beam, the beam energy dictates the shielding need. In this case ceiling and walls of an irradiation cell are generally more than 2.2 m thick.

In a most commonly used wet storage type irradiator, the radionuclide source when not in use, is stored under water. Water works as shield and is generally a preferred material due to being cheap and easily available. E beam accelerators can be switched `on-off' as and when required, however shielding is required during operation. Due to high penetration power of gamma sources, bigger size containers are amenable to radiation processing, however with electrons due to limited penetration thickness of product box becomes a limiting factor. To overcome this limitation, electrons are required to be converted to X-rays. However, poor conversion efficiency becomes a bottleneck from economical point of view. Type of food, dose to be delivered, and required throughput often determine the choice of an irradiator. If suitable conveyer system to deliver the food specific required dose is integrated in E beam facility, due to comparatively very high dose rate than gamma ray, E beam can be considered to be very much suitable for the high- volume food products. Besides, while handling high volume food products, it is understood that continuous mode of operation can be more effective than that of batch mode.

3. Biological effect of irradiation rendering food preservation

For radiation processing, food samples (either packed or in bulk) are kept in containers and moved by a conveyor into irradiation cell. In this process food is exposed for fixed duration (depending upon the required dose to be delivered) to radiations coming out from the radiation source. Radiation treatment works by directly interacting with the target molecule(s) or indirectly through radiolytic products of water as later is the major ingredient in most of the food products. Among these, hydroxyl radical is one of the highly reactive species that primarily interact with the organic molecules present in foods as well as food contaminating organisms. Nucleic acid being the largest biomolecule in any cell becomes the most affected target in food matrix too. By these interactions radiation treatment inactivates and destroys the essential biomolecules of insects, parasites, and microorganisms. Although radiation treatment results in inactivation of the food contaminating microorganisms, insects and pests, however these changes are minimized in foods due to presence of different radical scavenging moieties in the food matrix. Food matrix majorly comprised of macronutrients such as carbohydrates, lipids, amino acids, and proteins and minor nutrients such as vitamins, minerals etc. Carbohydrates (polysaccharides, oligosaccharides and monosaccharides) are comparatively less sensitive. Monosaccharides are linked to each other with glycosidic bonds and some of these bonds may break once exposed to radiation, however, this does not affect the nutritional value of carbohydrates but merely leads to depolymerisation. In case of proteins electron transfer do happen. Amino acid chains (polypeptides) may get altered in the presence of water present in the food. This could lead to denaturation of protein or breakdown to oligopeptides/ free amino acids. In the oxygenic environment, radiation treatment can accelerate lipid peroxidation due to the generation of free radicals and hydrogen peroxides. Therefore, radiation processing is preferably used for low fat foods. Impact of its interaction on food ingredients is minimized due to presence of diverse types of radical scavenging moieties present in the food. Whatever minor changes are happening in the food upon radiation treatment, has not found to be causing any issues with food safety or wholesomeness.

4. Applications of radiation processing in food preservation

For food irradiation applications, there is a basic and logical criterion to decide the minimum absorbed dose (D_{min}). It should be sufficient to achieve the envisaged technological purposes. Similarly, the maximum absorbed dose is decided based upon the observations that it should be lesser than which would compromise the overall quality attributes. The impact of extreme end of any treatment is not unique to radiation processing else it applies equally to other food processing technologies too. For example, over cooking of food or over boiling of milk may alter their taste. In general, 10 kGy of the maximum absorbed dose delivered to a food is enough to achieve most of the legitimate technological purposes, however in certain cases treatment of food with even higher doses may be required. Such applications at higher doses have been endorsed by international statutory organizations (Codex Standard, 2003; ICGFI, 1991). Codex Standard has also recommended re-irradiation of certain foods in very exceptional cases. This applies to the foods with low moisture content such as cereals, pulses, dehydrated foods and other similar commodities which are subjected to radiation treatment for controlling insect infestation. Rest other types of foods are not recommended to be re-irradiated.

Depending upon the required absorbed dose for achieving specific objectives, the radiation processing of food is classified into the following three groups.

(a) Food irradiation applications requiring lower absorbed dose (less than 1 kGy),
(b) Food irradiation applications requiring medium absorbed dose (1-10 kGy) and
(c) Food irradiation applications requiring high absorbed dose (more than 10 kGy)

Absorbed radiation dose is measured in the unit of Gray (Gy) i.e. absorbed energy of 1 Joule per kilogram of the matter.

4.1. Low Dose (< 1 kGy) Applications

4.1.1 Shelf- life extension in bulbs and tubers through inhibition of sprout formation

After harvest, onions have a dormancy period for 4-6 weeks whereas potato has nearly 14 weeks of dormancy. During this period these produces are not responsive to change in environmental condition and therefore hardly any changes are visible. During dormancy period bulbs and tubers do not grow, and wait for necessary environmental conditions such as temperature, moisture, and nutrient availability. Also the activities of cytokinins, gibberellins, and auxin, the endogenous hormones, are very low, and the activity of their inhibitor is high. However, once the dormancy breaks depending upon the storage condition leads to quality deterioration and losses. Inhibition of sprout formation in potato (tubers), onion (bulbs), ginger (rhizomes) and taro (corms) is achieved at the radiation dose of 0.06 to 0.15 kGy (Gautam & Tripathi, 2016). If stored in controlled condition radiation treated onions and potatoes can be preserved up to 7-8 months (Fig. 1). There is major issue of weight loss in onions and shrinkage in case of potato. These issues can be easily addressed by radiation processing followed by cold storage in controlled conditions.

Figure 1. Control of post-harvest losses in onion by radiation processing

4.1.2. Preservation of grains (Cereals and pulses) through Insect disinfestations

Insects, rats, birds, mites, bacteria, and fungi are live factors that are responsible for the losses of grain during storage. Moisture in grains, humidity (in the air), and temperature are the variables that impact the losses of grain during storage. Each of these factors can cause rapid decline in germination, malting quality, baking quality, color, oil composition, and many other quality characteristics. Agricultural produce is often get infested with insect pests and microbial pathogens during storage. Microorganisms thrive in high moisture levels and their presence can lead to mold growth, grain spoilage, and mycotoxin contamination. On the other hand, low moisture levels can also compromise quality, resulting in cracked grains that are more susceptible to damage during handling and transportation. Stored grain pests cause serious post-harvest losses, almost 9% in developed countries to nearly 20% or more in developing countries. Post-harvest losses in the developing counties is due to improper and unscientific storage infrastructure. This allows the easy damage by insects, rodents, and micro-organisms. Nearly 14 -million tons of grains have been reported to undergo annual storage losses in India. In this losses due to insects (primarily the lesser grain borer, rice weevil and rust red flour beetle) account for major losses. Many grain pests preferentially eat grain embryos. This leads to the reduction in the protein content of grains and also their poor germination efficiency.

The grain weevils (Curculionidae) are well-known as major primary pests of stored cereal grains. They are able to establish themselves on whole, undamaged grains of maize, sorghum, rice and wheat so long as the grains are not exceptionally dry. In international trade of agricultural commodities pest infestations is one of the major constraints. The presence of pesticide(s) residues in the food is of profound concern to consumers. Therefore, legislation has been implemented to ensure compliance with Maximum Residue Levels (MRL) of chemicals in food worldwide. Educated consumers and implementing agencies are well aware of the adverse effect of current practices of chemical fumigation in preservation of grains. Therefore, fumigants such as methyl bromide (MB) and ethylene dibromide (EDB) have been banned or recommended to be phased out by various international statutory organizations. Malathion and Aluminium phosphide are being used as prophylactic measures during grain storage in India. These pesticides are known to have negative effects on health and environment. On the other hand radiation processing has excellent potential to address these concerns and provides a safe, scalable and user friendly physical alternative to preserve grains without any use of harmful chemical fumigants (Fig. 2). Pre- and post-irradiation processing and storage methodologies are required to be integrated in commercially sustainable way for its realization at larger scale using modern storage infrastructure such as silos.

4.1.2. Ripening delay in fruits and vegetables

Approx. 138 million tons of vegetables and 105 million tons of fruits are produced in India annually. The quantum is second highest after China. Fruits are either climacteric or non-climacteric in nature. Climacteric fruits have increased respiration rate along with a burst of ethylene biosynthesis after harvest during ripening process whereas non-climacteric fruits do not ripen after harvesting and do not display any increase in the rate of respiration. Climacteric fruits once radiation treated at pre-climacteric (hard mature) stage at the absorbed dose of ≤0.75 kGy, the ripening get delayed by nearly seven days and also quarantine pests are destroyed.

Agricultural produce destined to export needs to be free of pests else that could harm the agricultural crops/ harvest of the importing countries. Therefore, radiation processing as a phytosanitary treatment was accepted by many importing countries including USA. India started exporting radiation treated mango to USA since 2007 after the gap of 18 years. In 2024 it exported nearly 3000 tons of mangoes after irradiating at four commercial facilities. Radiation processed Indian mangos were also exported to Australia, South Africa and Malaysia. Besides, recently a technology has been developed at Food Technology division, BARC, Mumbai which helps in achieving the delayed ripening of mangoes to enable the sea-route shipment.

Figure 2. Control of post-harvest losses (due to insect infestations) in grains by radiation processing

The SOP has been approved by United States Department of Agriculture. A large trial containing a shipping container having around sixteen tons of Kesar mangoes were processed at Maharashtra State Agriculture Marketing Board (MSAMB) - Irradiation Facility Centre (IFC), Vashi, Navi Mumbai as per BARC developed SOP and shipped to USA in 2022. Mangoes were found with good cosmetic appeal and excellent physical condition. The shipment was cleared by the regulatory agencies namely, USDA-APHIS (USA Department of Agriculture - Animal and Plant Health Inspection Service) and USFDA (USA- Food and Drug Administration). The fruits were marketed successfully in USA (Fig. 3). Sea-route shipment would reduce the freight charges to nearly 1/8th in comparison to air shipment. Other radiation processed fresh fruits and vegetables can also be stored for extended period in controlled storage conditions. For example, green mature tomato can be stored at 10-13^{0}C in unripe stage till 2 months once irradiated at D_{min} of 650 Gy.

Figure 3. Delayed ripening in mangoes and phytosanitary treatment to overcome quarantine barrier of trade

4.2. ***Medium Dose (1-10 kGy) Applications***

4.2.1. *Preservation of sea-foods, meat and meat products*

India is one of the major producers and exporter of sea-foods. Because of improper storage conditions and pathogenic contaminations during handling and processing practices freshly caught fish is prone to rapid spoilage. Important benefits of radiation processing are in preservation of chilled fish and meat products which is otherwise stored in frozen conditions. Besides saving electricity consumption, such chilled stored products have much better overall qualities than the frozen counterpart. Fish such as Indian Salmon, Bombay duck, Pomfret, and shrimp has storage life of 7-10 days at ice temperature. Radiation processing at 4-7 kGy and storage at 1 to 2^0 C increases its shelf life to around a month. Meat and meat products have a storage life of around 7 days at 0-3^0 C, which can be extended up to one month upon subjecting to radiation dose of 4-7 kGy and storage at 1 to 2^0 C. Radiation processing is also suitable for preserving intermediate moisture fish and meat products.

4.3. High Dose (>10 kGy) Applications

4.3.1. Hygienization and microbial decontamination of spices

Spices often get contaminated with insect eggs and microbial pathogens during post-harvest processing. Contaminated spices results in spoilage of food upon addition and therefore risk to consumers. For India the issue is of prime importance as it is the major spice producing and exporting country in the world. The issue becomes more worrisome when insect infested or microbe contaminated spices get converted into spice powders due to wrong commercial practices. Radiation processing at Dmin absorbed dose of 6 kGy can resolve these issues while retaining the quality attributes of spices and thus ensuring its safety (Fig. 4). In India most of the existing 28 food irradiation plants are engaged in radiation processing of spices and allied products.

Non-irradiated

Irradiated ($D_{min.}$: 6 kGy)
Shelf Life: 1 year

Figure 4. Microbial decontamination and insect disinfestations in spices using radiation processing.

5. Wholesomeness, Nutritional Adequacy and Safety of Radiation treated Foods

Attributes of food such as safety, nutritional sufficiency, and organoleptic attributes (flavor and aroma) lead to its wholesomeness. Concerns about induced radioactivity; safety associated to microbes; nature of interacting chemical moieties and end products; as well as nutritional adequacy were the key parameters thoroughly investigated worldwide in context of wholesomeness of radiation treated food since last six decades (JECFI, 1981; Roberts, 2014 & 2016; WHO, 1994). At the energies of approved radiation sources, no induction of radioactivity is possible in atoms constituting food. Besides, nutritional loss was also very much insignificant in radiation processed foods. The microbiological concerns of radiation treated foods have been thoroughly investigated and it was observed that such foods do not lead to any changes in microbes which can make the food harmful. Further concern was related to the safety of irradiated food due to interaction of radiation with matter leading to formation of free radical(s) and radiolytic product(s). This has been thoroughly investigated and the findings concluded that there are no unique radiolytic products formed and most of the free radicals in the system disappear at the time scale of nanosecond. Thorough investigations further concluded that the free radicals or radiolytic products formed into the foods upon radiation treatment do not compromise to their safety (Diehl, 1995, 2002; Joint FAO/WHO Codex Alimentarius Commission, 1984; Lacroix & Follett, 2015). Subsequently many animal feeding studies and with human volunteers did not show any adverse effect. However, for information to the consumers about the value addition upon radiation processing of food, 'Radura' logo has been adopted (Dieter, 2009). Recent mutigenerational study conducted to evaluate the genotoxic safety of radiation treated foods in various model systems at Bhabha Atomic Research Centre (BARC), Mumbai, India too affirmed the earlier observations (Hajare et al., 2017; Saxena et al., 2018).

6. Regulatory approval

In India, Atomic Energy (Control of Irradiation of Food) Rules were notified in 1991. In 1994 Government of India amended Prevention of Food Adulteration Act (1954) Rules and approved irradiation of onion, potato and spices for domestic market. In 1998 and 2001 additional food commodities were approved. In 2004 'Plant Quarantine (Regulation of Import into India) Order, 2004', included irradiation as a phytosanitary treatment. In 2006 signing of a Frame Work Equivalence Work Plan agreement between USDA- APHIS and the Ministry of Agriculture & Co- operation, Govt. of India took place resulting in Phytosanitary treatment of mango for export to USA. In the year 2016 Government of India gazette notified the Generic 'food- class' based approval of Radiation processing of food and Allied Products Rules, 2012.

The USA FDA approved irradiation (Table 1(A) and Table 1(B)) of wheat and wheat products for insect control with a dose of 0.2-0.5 kGy in 1963, and in the same year cleared sterilization of vacuum-packed canned bacon with a dose of 45-56 kGy. Permission for irradiation of white potatoes for inhibition of sprouting with a dose of 0.05-0.1 kGy was granted in 1964. Irradiation of potatoes had been approved in the Soviet Union in 1958, followed by Canada in 1960. Between 1964-67 USFDA approved radiation processing of materials used in food packaging. Joint FAO/IAEA/WHO Expert Committee on safety & wholesomeness of Food Irradiation (JECFI) in 1976 approved several irradiated foods and recommends that food irradiation be classified as a physical process. In 1980 JECFI approved radiation processing of foods at a maximum average dose of 10 kGy and later FAO/WHO/IAEA recommended doses above 10 kGy (Codex, 2003; FAO/WHO/IAEA, 1999; WHO 1966, 1981, 1994, 1999). In 1983 USFDA and Canadian Health and Welfare Department approved radiation based microbial decontamination of spices. To control trichinosis, US FDA approved radiation pasteurization of pork in the dose range of 0.3 to 1 kGy in 1985. In 1986 USFDA approved radiation treatment up to 1 kGy for fruits, vegetables and some other foods. Between 1990-92 the USA government accorded approval for treatments of poultry to eliminate foodborne pathogens in the dose range of 1.5 to 3.0 kGy.

As per the Codex Standard, the relevant shipping documents pertaining to irradiated foods (open or pre-packaged) shall give appropriate information to identify the registered irradiation facility, the date(s) of treatment, irradiation dose and lot identification.

7. Radiation processing facilities

In India, the first pilot radiation processing facility, the Food Package Irradiator was commissioned in 1967 in Food Irradiation Processing Laboratory (FIPLY). After that DAE established two plants, Krishi Utpadan Sanrakshan Kendra (KRUSHAK) at Laslagaon, Nashik for low dose applications and Radiation Processing Plant (RPP), Vashi for high dose applications. State Governments of Mharasshtra, Gujarat, Tamil Nadu and Andhra Pradesh too made one plant each. So far, 22 plants have been established under private entrepreneurship, making total number to 28 by 2024. Besides, many plants are in construction stage including one by State Government of Bihar.

8. Deployment of irradiation technology at the user end

As far as its wide spectrum usefulness is concerned non-other food preservation technologies have such a wide spectrum positive impact as radiation technology. Besides the radiation processing being a non-thermal process its adverse impact on the food subjected to irradiation is almost negligible. USA is importing fruits subjected to radiation treatment as phytosanitary measure from many countries worldwide including mango form India since 2007 (Hallman et al., 2016; Sharma, 2008). China too is using radiation preservation of huge volume of food for domestic consumption. Vietnam is involved in trade of substantial quantity of radiation processed animal -based foods (Kume & Todoriki, 2013). The confidence generated in this technology through extensive R&D has made its endorsement by many international statutory organizations such as WHO, FAO, IAEA, USDA, FSA&NZ, and FSSAI and further acceptance for food processing applications by more than 70 countries worldwide including India.

Although Radiation Processing of Food is more than a century old technology, and having all its success story as detailed above, its deep penetration in the user community is still awaiting. The major bottlenecks in its larger dissemination are capital cost incurred for setting up an integrated Food Irradiation Plant (FIP) including storage infrastructures (e.g. cold storages for perishable food products or silos for grains). The technology is excellent for High Value & Low Volume (HVLV) products (e.g. spices, herbals etc.). But there are limitations of throughput with high volume products such as grains, fruits and vegetables. Therefore, there is need of extensive R&D on engineering design to cater the need of irradiation of these high volume produces in a cost-effective manner. Many such agricultural products need to be radiation processed within certain time period after harvest due to expected physiological changes happening in the commodity or environmental impact happening during storage. Some examples are break of dormancy in onion and potato within few months of harvest and insect infestation happening in grains within few months of post-harvest storage. Therefore, such commodities need to be radiation processed prior to onset of these deterioration process and thus limiting the throughput of a FIP. Besides, another important need is that the benefits of technology should be shared down the line to the farmers. This is possible if FIPs are located close to farming areas which would reduce the transportation cost to the greater extent. Besides, farmers should have benefits of irradiation of agricultural produce and storage in the monetary terms. For this, financial burden on farmers in terms of irradiation, handling, and storage cost should be minimized through proper mechanism. Bringing the Farmers

Cooperatives (FCOs) or Farmer Producer Organizations (FPOs) in this domain could be another way to address the said concern.

9. Food Security from Socio-economic perspective

Unorganized agriculture sector makes the conditions of farmers particularly in developing countries quite worrisome. They are the ones which get most affected by demand supply imbalance of agri-produce. If production is huge farmers will not get due financial benefit as supply will be huge and therefore low pricing. In reverse case when production is less and therefore supply, the cost of produce will be high but benefits will not reach to the farmers as in general they lack storage facilities and infrastructure. Keeping this in consideration an issue is being brought here to all concerned to find an amicable solution pertaining to Agro-Economical Pyramid particularly with respect to the farmers (the producers).

9.1. Agro-Economical Pyramid

Flow of energy in the ecosystem is ideally represented through the food chain wherein the plants are the producers. These producers are consumed by the primary consumers and the primary consumers by the secondary consumers and so on (Fig. 5). Similarly pyramid of monetary flow and therefore financial health is being proposed here in economic terms primarily with respect to the agriculture sector.

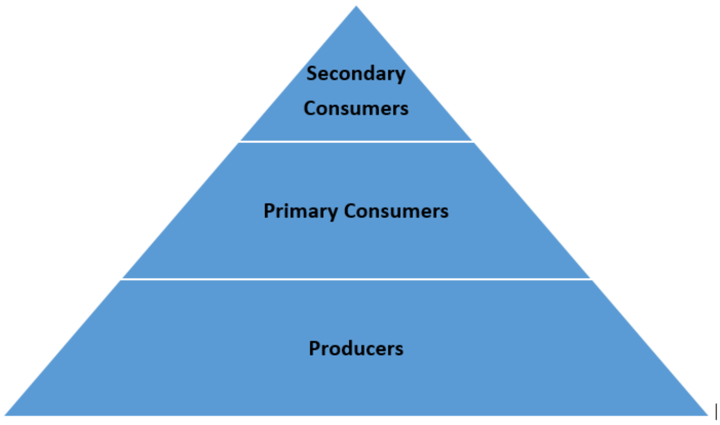

Fig. 5. Generalized structure of a food chain

When one examines an energy pyramid, the base of a pyramid is always bigger than the levels above it, and each individual level is smaller than the one below. As the base is always bigger this makes the entire structure stable.

Opposite is the case of agro-economical pyramid where the base of the pyramid is smaller than the levels above it, and each individual level is bigger than the one below. As the base is smaller this makes the entire structure unstable and therefore the agro-economy and in other words farmer's economic health (Fig. 6). In majority of the agriculture sector major returns coming out of the sale of raw or processed products are largely gained by those placed in the upper level of the agro-economical pyramid. In the developing nations this distribution has even higher disparity.

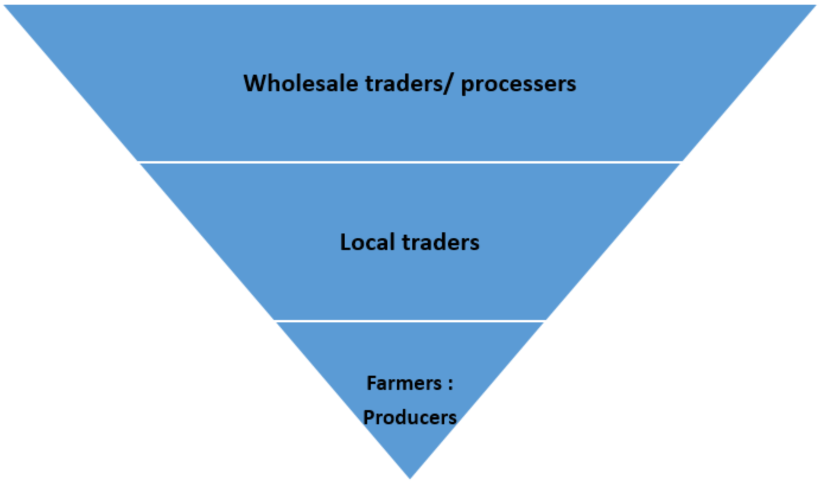

Fig. 6. Flow of financial gains in the agro-economical pyramid

9.2. Limitations negatively affecting the producer's economies

Production and profitability are generally beyond the control of the producer. Factors such as weather condition, pest prevalence, disease spread and market conditions affect the production and profit. Market conditions include selling prices, labour availability, food safety concerns, and expected quality standards from consumer's perspectives. A larger quantity of fruit and vegetables are under-rated. This happens because the product does not meet market driven quality specifications during the supply management particularly in terms of cosmetic components (e.g. color, shape, size) as well as qualities required for successful transport in terms of level of ripeness etc.

10. Reversal of the Agro-economical pyramid

It is not the case that the agro-economical pyramid cannot be reverted to provide stability. What it requires the scientific pursuit to strengthen the producers (e.g. farmers) to have capacity to control the demand supply balance in its favour through adoption and integration of modern technologies in their agro-management. White revolution in the milk sector is one convincing and remarkable examples.

11. Milk industry in India making pyramid stable and impact thereof: A Case Study

Operation Flood program was started in 1970 by National Dairy Development Board (NDDB) under the aegis of Government of India. This led to White revolution and transformed India from a milk-deficient nation into the world's largest milk producer. Not only milk production but dairy farming became the India's largest self-sustainable rural employment generation program. National milk grid linking producers throughout India to consumers in over 700 towns and cities were created. This helped in reducing seasonal and regional price variations while ensuring that producers get a major share (nearly 60-70%) of the profit by eliminating the middlemen. Therefore, structure of pyramid pertaining to flow of financial gains in the milk sector is stable in upward triangular form (not inverted as seen in case of agriculture sector). The fundamental basis behind this success is active role of village milk producers' co-operatives. It procures milk and provide inputs and services. Besides, it has also made modern management and technology including chilled transportation available to all the members across the country.

12. Conclusion & the Way Forward

'An intriguing question which applies to most of the technologies is true here also if food is being preserved using radiation technology how much financial gain it may render to the concerned stakeholders including growers.

While looking into the success story of this technology it is very clear that the radiation technology is very much successful and proven in the case of high value food commodities including spices. For mango too its export helps in good revenue generation and hence there is larger use of radiation technology for mango export from India as well as other mango producing countries.

Many a times users give credit to the regularity compulsion imposed by the importing counties but it is worth highlighting that '*Any regulatory compulsion can't sustain a business unless it is commercially profitable'.*

'Why did radiation technology make limited penetration into the domestic market?'

This remained the unresolved query and often asked in many scientific forums. Often poor consumer acceptance is blamed for this situation. How much the answer is justified in the conditions where consumers didn't get the option to select the radiation treated food products from the shelves on the market. Again why consumers should prefer such products unless they are well informed about the precise benefits being gained upon its consumption. This can be achieved through deployment of proper and effective information sharing tools having wider and large scale impact including print and electronic media. Therefore, outcomes of food product specific R&D highlighting the benefits of radiation processing based upon scientific merits needs to be brought out. Besides commercial or quality (value addition) gains expected while using this technology also need to be promptly and equally highlighted.

'There is utmost need to address the issue of preservation of Agri-produce in totality from Farm to Market. Selecting an intermediate stage of supply chain may not resolve the issues comprehensively and thus will affect the dynamics of potential benefits of food irradiation technology'.

In nutshell 'An introspecting thought process by concerned stakeholders including associated policy making Government bodies, Concerned R&D institutes, FCOs, FPOs, as well as private firms at various stages of post-harvest management of agricultural produce is the need of the day to deploy the modern science based greener technologies including food irradiation to address the national food and nutritional security!'

Acknowledgements

Contributions by Current and Former Scientists and Technical staffs of Food Technology Division, Bhabha Atomic Research Centre, Mumbai in the progress of National Food Preservation Program using Radiation Technology is duly acknowledged.

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Table 1 (A). Approval of Radiation Processing of Foods based upon Generic classes by the Government of India.

Class	**Food**	**Purpose**	Dose limit (kGy)	
			Minimum	Maximum
Class 1	Bulbs, stem and root tubers, and rhizomes	Inhibit sprouting	0.02	0.2
Class 2	Fresh fruits and vegetables (other than Class 1)	Delay ripening	0.2	1.0
		Insect disinfestation	0.2	1.0
		Shelf-life extension	1.0	2.5
		Quarantine application	0.1	1.0
Class 3	Cereals and their milled products, pulses and their milled products, nuts, oil seeds, dried fruits and their products	Insect disinfestation	0.25	1.0
		Reduction of microbial load	1.5	5.0
Class 4	Fish, aquaculture, seafood and their products (fresh or frozen) and crustaceans	Elimination of pathogenic microorganisms	1.0	7.0
		Shelf-life extension	1.0	3.0
		Control of human parasites	0.3	2.0
Class 5	Meat and meat products including poultry (fresh and frozen) and eggs	Elimination of pathogenic microorganisms	1.0	7.0
		Shelf-life extension	1.0	3.0
		Control of human parasites	0.3	2.0
Class 6	Dry vegetables, seasonings, spices, condiments, dry herbs and their products, tea, coffee, cocoa and plant products	Microbial decontamination	6.0	14.0
		Insect disinfestation	0.3	1.0
Class 7	Dried foods of animal origin and their products	Insect disinfestation	0.3	1.0
		Control of moulds	1.0	3.0
		Elimination of pathogenic microorganisms	2.0	7.0
Class 8	Ethnic foods, military rations, space foods, ready-to-eat, ready-to-cook/ minimally processed foods	Quarantine application	0.25	1
		Reduction of microorganisms	2	10
		Sterilization	5	25

Table 1(B). Approval of Radiation Processing of Allied Products by the Government of India.

Class	Food	Purpose	Dose limit (kGy)	
			Minimum	Maximum
1.	Animal food and feed	Insect disinfestations Microbial decontamination	0.25 5.0	1.0 10.0
2.	Ayurvedic herbs and their products, and medicines	Insect disinfestations Microbial decontamination Sterilization	0.25 5.0 10	1.0 10.0 25
3.	Packaging materials for food/allied products	Microbial decontamination Sterilization	5.0 10.0	10.0 25
4.	Food additives	Insect disinfestations Microbial decontamination Sterilization	0.25 5.0 10	1.0 10.0 25
5.	Health foods, dietary supplements and nutraceuticals	Insect disinfestations Microbial decontamination Sterilization	0.25 5.0 10	1.0 10.0 25
6.	Body care and cleansing products	Microbial decontamination Sterilization	5.0 10	10.0 25
7.	Cut flowers	Quarantine application Shelf-life extension	0.25 0.25	1.0 1.0

About the Authors

Shri S. Gautam joined Food Technology Division, BARC in 1995 through prestigious Training School Program. He completed his doctorate degree in science from University of Mumbai, and post-doctoral studies (2005-07) at University of Medicine and Dentistry, New Jersey, USA. Using radiation technology Dr. Gautam has worked extensively on the preservation of foods, development of special purpose ready-to-eat meal, as well as on the understanding the potential nutraceutical applications of dietary ingredients. He has carried out fundamental studies to reveal the mechanism of cell death in stressed bacterial cells. Dr. Gautam has served as the Chief Scientific Investigator for IAEA Coordinated Research Project (CRP) and members of National Project Team of different IAEA projects. He was instrumental in setting up a litchi treatment plant for preservation of litchi fruits at Muzaffarpur, Bihar. Dr. Gautam has 143 publications in peer reviewed journals and books, alongside many abstracts in conferences. He is currently serving as Head, Food Food Technology Division, Bhabha Atomic Research Centre, Mumbai and also Professor at Homi Bhabha National Institute (HBNI), DAE, Trombay, Mumbai. Dr. Gautam has been awarded highly prestigious DAE-Homi Bhabha Science & Technology Award (2016) for outstanding contributions in the area of Food Science and Technology as well as DAE Group Achievement Awards twice (2009 & 2011). Dr. Gautam is a fellow of Maharashtra Academic Sciences. He was associated with FSSAI as Chairman and member of scientific panels. Recently, Dr. Gautam addressed the Scientific Forum of IAEA General Conference at Vienna on the theme Atoms for Food.

Chapter 5: Nuclear Agriculture: Developments and Accomplishments

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***Abstract**: Technological innovations in agriculture have significantly boosted food grain production, addressing the demands of a growing global population. Enhanced productivity has been achieved through the development of climate-resilient crop varieties with improved quality and resistance to biotic and abiotic stresses. In India, the agriculture sector contributes 17% to the GDP, with food grain production reaching an all-time high of 329.7 million tonnes in 2022-23. Despite these advancements, challenges such as unpredictable weather, declining soil health, rising temperatures, and emerging pests and diseases continue to threaten food security. To combat these issues, plant breeders are leveraging advanced genomic, phenomic, and crop modeling tools, alongside traditional breeding methods, to develop location-specific crop varieties. Mutation breeding, in particular, has emerged as a powerful technique for generating genetic variability and improving traits such as drought tolerance, disease resistance, and nutritional quality. Over 3,365 mutant varieties have been registered globally, with more than 1,000 varieties successfully deployed in agriculture. Physical mutagens like gamma rays and chemical mutagens such as ethyl methanesulfonate (EMS) have been instrumental in inducing beneficial genetic changes. Recent advancements in high-throughput genomic tools, including whole-genome resequencing and molecular markers, have further accelerated the identification and characterization of desirable mutations. In India, the Bhabha Atomic Research Centre (BARC) has developed 70 mutant crop varieties, including high-yielding groundnut, mustard, and rice varieties, contributing significantly to national food security. These innovations underscore the critical role of mutation breeding and genomic technologies in developing sustainable and resilient agricultural systems to meet future food demands.*

1. Introduction

Technological innovations in the agriculture sector have led to an unprecedented increase in the food grain production for the ever-growing population. Enhanced productivity among the food crops is due to the concerted effort by the plant breeders in developing climate-resilient crop varieties with improved quality and resistance to biotic/abiotic stresses. Agriculture sector has transformed the Indian economy with 17% contribution to GDP and an all-time high food production of 329.7 million tonnes during 2022-23 (Kumar et al., 2024). Today, India is the world's leading producer in milk, lentils, jute, and spice and second largest producer of pulses, farmed fish, eggs, coconut, sugarcane and vegetables (Pathak et al., 2022). However, often food production is affected by several factors, such as uncertainties of weather, declining soil health, increasing atmospheric temperature, and the emergence of virulent pests and diseases. To address these problems, crop breeders are relentlessly working on developing location-specific varieties that can withstand these adversities by applying new breeding methods coupled with new genomic, phenomic and crop modelling tools (Cooper et al., 2014). In this context, specific traits such as drought and submergence tolerance, disease resistance and improved nutritional quality have been introgressed in the popular varieties of various field crops for enhanced productivity.

Over the past 25 years, several technologies have become milestones in solving the problems/complexities associated with plant breeding & crop genomics. Some of them include, speed breeding, introgression from wild crops through recombination breeding, mutation and marker assisted breeding techniques for enhancing crop produce. Among these methods, mutation breeding is used to generate genetic variation, break negative linkage and improve yield/nutritional content or resistance to pests/diseases in popular cultivars (Novak and Brunner, 1992). Specifically, plant mutagenesis helps in inducing beneficial mutations so that the enhanced variation aids in the selection of superior genotypes with novel traits (Kharkwal, 2012). Spontaneous mutations are very rare and random in nature, which make them more difficult to use in plant breeding programs (Lonning, 2005). In this way, induced mutations using diverse range of mutagens have become prominent method in bringing heritable changes among the qualitative and quantitative traits.

2. Mutation breeding for crop improvement

Ionizing radiations and chemical mutagens have been used to bring heritable changes in crop traits. In order to breed for stable mutations, the process involves exposing the seeds or cuttings of a given plant to a radiation source to induce genetic mutations. The irradiated material is then cultivated to produce a plantlet and subsequently selected and multiplied, if it shows unique and desired traits. By monitoring plant growth, one can identify and select variants with the desired characteristics and develop stable varieties for direct use or as parental material in cross-breeding program. Mutation breeding has become the most successful field of application of nuclear techniques by developing more and more mutant crop varieties, which have been released to farmers and contributed to the state and national food security of several countries (Shu et al., 2012). Over 3,365 mutant varieties have been registered in the Mutant Variety Database (MVD) of the International Atomic Energy Agency (IAEA), and more than 1,000 new varieties have been used and promoted worldwide (Liqiu et al., 2021).A wide range of unique characters, including yield, flowering and maturity duration, plant architecture, seed quality, and tolerance to biotic and abiotic stresses have been improved in the mutant varieties developed so far.

3. Mutagenic agents

Mutations can be induced by variety of mutagenic agents, including physical (radiations) and chemical substances, which can directly modify the DNA sequence, causing heritable changes in the genetic material. Over the last century, physical mutagens, such as fast neutrons, UV, X-ray, gamma radiation, electron beams and chemical mutagens, including N-methyl-N-nitrosourea (MNU), sodium azide, methyl methanesulfonate (MMS), or ethyl methanesulfonate (EMS), have been widely explored to initiate genetic changes in key traits(FAO/IAEA, 2018). Ionizing radiations cause a mixture of major chromosomal changes such as deletions and point mutations, whereas the most commonly used chemical mutagens (e.g., NaN_3, EMS/MMS, MNU) can cause single base substitutions (transition and transversions) (Szarejko et al., 2017).Unlike classical gamma rays and X-rays, which are essentially electromagnetic waves, the new category of mutagens represented by accelerated heavy ions or protons are charged particles and can deposit more energy along the ion track. Additionally, they can bring a higher mutation frequency and spectrum at a relatively low dose due to their high linear energy transfer (LET) (Asaithamby and Chen, 2011). The structural changes in the DNA molecule is relatively less amenable to repair, leading to the generation of sticky DNA fragments, formation of more chromosomal rearrangements and major deletions. These rearrangements in turn generate more combinations of gene mutations and lead to higher mutagenic efficiency (Pastwa et al., 2003).

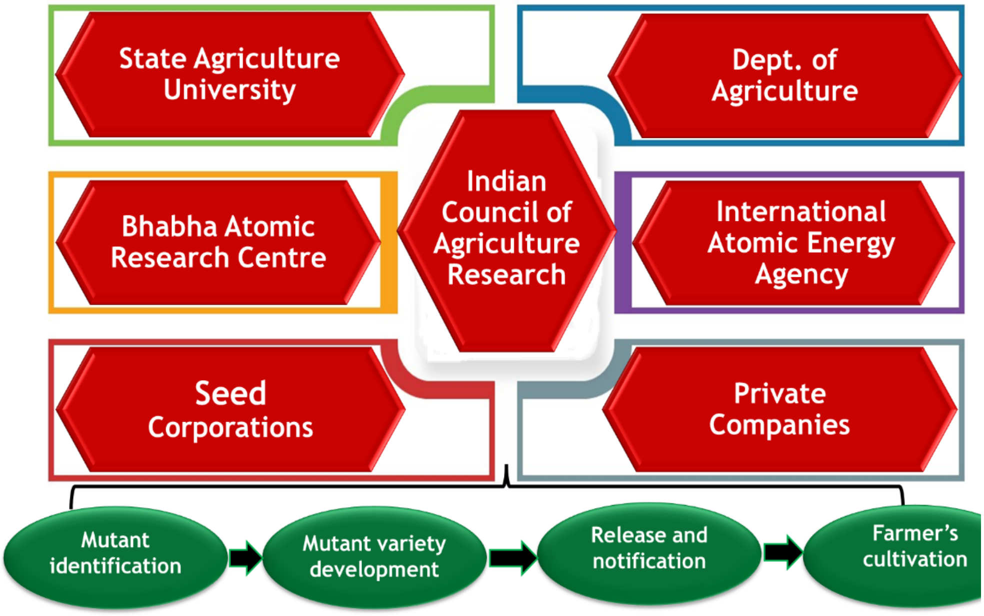

Figure 1. Key institutes involved in the development of mutant varieties

4. Plant mutagenesis and varietal development

Physical and chemical mutagens are often used in conjunction with other molecular techniques in order to genetically modify the existing cultivar with altered phenotype (Mba, 2013). Once the genotype is chosen, a homogenous seed stock with optimum moisture content is subjected to radiosensitivity testing to determine the optimum dose levels of mutagen for mutation induction (FAO/IAEA, 2018). For practical purpose, it is advisable to use three doses (± 20% of the optimal dose) of the chosen mutagen, found through the radio-sensitivity tests (Kalpande et al., 2021). The irradiated seeds are immediately taken for space planting following all the normal agronomic practices to yield the M1 generation. The selected variants are harvested as single-seed bulk/modified bulk methods to produce M_2 seeds. In M_2 generation, depending on the availability of land and resources, M1 harvested seeds are sown as plant-to-row progenies, which will help to identify recessive mutations segregating in the same progeny. It is advisably to grow large M_2 population to identify rare mutations with the desired phenotype (Sahu et al., 2020). Along with phenotypic selection, breeders can also use other molecular methods to rapidly screen large M_2 populations for special traits, such as disease/pest resistance and abiotic stresses. Once the putative mutants are identified, they should be harvested individually and planted in the next (M3) generation as progeny rows. Progeny tests are essential for the identification and validation of mutant traits in the M_3generation to establish the heritability of the trait (Oladosu et al., 2016). In the subsequent generations, the putative mutants can be validated and stabilized through self-pollination for most of the quantitative traits. In the advanced generations, replicated yield and multi-location trials will help the breeder to establish phenotypic uniformity and stability to counteract the variation due to the genotype x environment interactions (Xu et al., 2017). The top-performing mutant line may be advanced to adaptive trials at the university and state level and subsequently identified as a stable mutant variety (Fig: 1). Subsequently, after the release and notification, foundation/certified seeds will be distributed to the farmers by the state seed agencies or agriculture universities for commercial cultivation.

The overall procedure of developing a stable cultivar with desired mutation is a long-drawn process. The first generation of mutant cultivars described above can be developed largely following the classical methods of mutation induction followed by pedigree method of selection. The second-generation mutant cultivars include those involving a mutant and a germplasm/landrace in all cross combinations, followed by selection and stability analysis.

5. Genomic tools for mutant characterization

Stable mutant character identified by phenotypic screening should be characterized at molecular level to understand the genetic basis of the casual mutation. In field crops, where the sequenced genomes or reference sequences are available, novel mutant traits can be characterized using a combination of whole-genome resequencing, linkage maps, and transcriptome analysis providing a comprehensive information on changes in the gene expression in comparison with wild-type. Variety of molecular markers such as single nucleotide polymorphisms (SNPs), microsatellite markers, or various DNA rearrangements that can be detected by DNA sequencing, PCR, Southern blot, MALDI-TOF, or other hybridization techniques are also used in these analyses (Holme et al., 2019). Once the genetic inheritance and molecular basis of the causative mutation is known, then the modified trait can be introgressed in to other breeding lines. Recently many high-throughput screening platforms are available, which can efficiently genotype large populations. Such methods will not only help in identifying mutations in the complex quantitative traits governing economically important characters but also aid in the development of climate-resilient and nutritionally superior crop varieties.

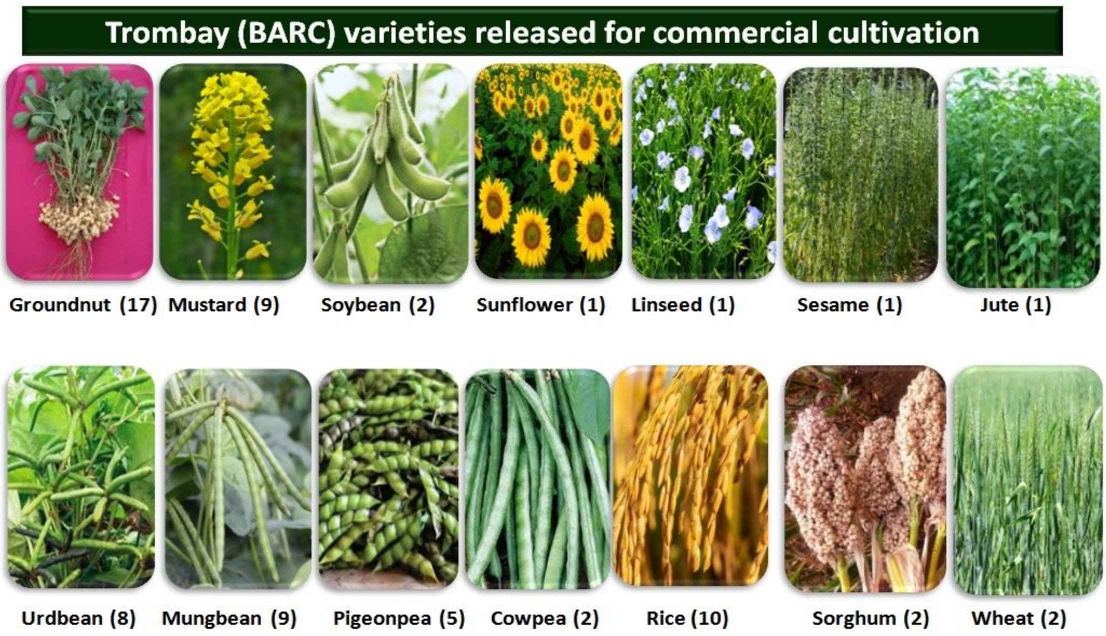

Figure 2. List of Trombay crop varieties released for the farmer's cultivation

6. Mutation breeding work at BARC

Harnessing the genetic variability in the economically important traits, BARC has so far released and notified a total of 70 crop varieties in crops that include groundnut, linseed, mustard, soybean, sunflower, mungbean, blackgram, pigeonpea, rice, wheat and sorghum (Fig: 2). In synergistic research collaboration with state agriculture universities as well as ICAR institutes, BARC is exploring the potential of radiation sources such as gamma rays and electron beams to develop location-specific varieties possessing early maturity, disease resistance, higher yieldswith improved nutritional qualities and abiotic tolerance. Some of the noteworthy mentions are the popular groundnut varieties (TAG 24, TG 37A) for high yield, early maturity and disease resistance; mungbean (TJM 3, TMB 37, TRCRM-147) and urdbean (TJU-339, and TRCRU-22) varieties for yield and resistance to yellow mosaic virus; rice (TCDM 1) for better grain quality and lodging resistance and TL-99 linseed variety with 2-5% linolenic acid for human consumption. In addition, vegetatively propagated crops like banana, pineapple and sugarcane have been improved for better productivity and disease resistance using gamma rays. Some of the success stories in these crops have been summarized here.

6.1.Oilseed crops

Towards achieving 'self-sufficiency' in the production of oilseeds, an important goal of the Vikasit Bharat Initiative, breeders are aiming to develop high-yielding oilseed varieties in soybean, mustard, sesame, linseed, and groundnut. Strategically diversifying oilseed crops and focusing on areas potentially lost to cereal cultivation could boost the country's edible oil production by 20% in the near future. In order to achieve this goal, several programs have been undertaken at agricultural universities and national institutes. Some of the innovative research initiatives by intervening genetic modification using diverse sources of radiation have been the priority areas of BARC. In this direction, key varieties in oilseed sector have been summarized as follows.

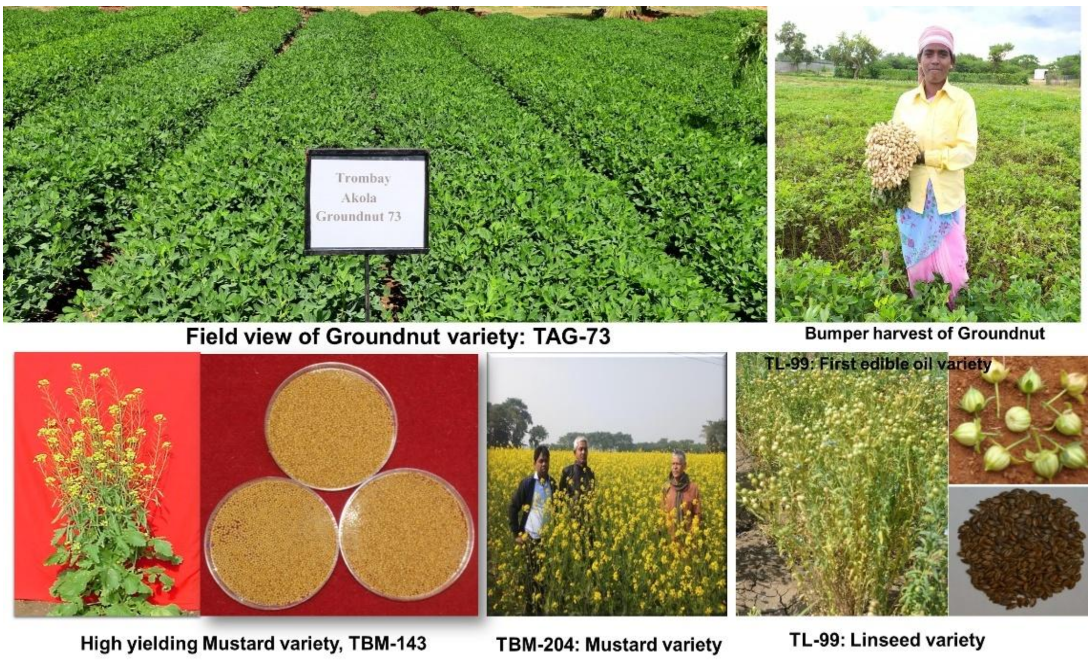

Fig: 3 Major Trombay oilseed crop varieties released for farmer's cultivation

6.1.1. Groundnut

Groundnut (*Arachis hypogaea* L.), an important oilseed and food crop, is rich in oil and protein. During 2023-24, India produced 6.91 million tonnes of groundnut from an area of 5.50 million hectares with major production from Gujarat state, followed by Rajasthan and Madhya Pradesh. Over the past years, per capita consumption of edible oil in the country has seen a moderate rise, reaching 19.7 kg/year (Gangadhara et al., 2023). The increased demand has significantly outpaced domestic production, leading to a heavy reliance on imports to meet both domestic and industrial needs. The production constraints could be lack of disease tolerant varieties, reduced productivity under rainfed conditions, climate change effects and effective management practices. Therefore, there is a need for strategic interventions to improve productivity, ensuring long-term sustainability.

In this direction, BARC had initiated a groundnut improvement program in 1957. The first groundnut variety, TG-1, was developed in 1973 by X-ray irradiation of the Spanish Improved cultivar. Subsequently, over five decades, 17 Trombay groundnut varieties have been developed for farmers' cultivation, which were improved for compact plant type, early maturity, drought tolerance, large seed, high oleic acid, and high pod yield (Table 1; Fig: 3). Recently, a new mutant derivative, Trombay Groundnut 88 (TG 88), was released as 'Chhattisgarh TrombayMungfali (CGTM)' in collaboration with IGKV, Raipur. CGTM is suitable for cultivation in rainy as well as summer seasons. Such TG varieties have also been used as donor parents for developing additional14 varieties by various state agricultural universities by harnessing their unique traits. Over the time, BARC, in collaboration with agricultural universities, has supplied more than 2500 tonnes of breeder seed indent of TG varieties to the various public and private sectors (Badigannavar et al., 2021). This in turn led to the multiplication of foundation and certified seeds to cater to the needs of prospective farmers. In this way, BARC has not only contributed to the national oilseed mission but also reflected on improving the economic status of the marginal farmers.

6.1.2. Mustard

Indian mustard (*Brassica juncea*) is predominantly cultivated in the states of Rajasthan, Uttar Pradesh, Haryana, Madhya Pradesh and Gujarat, as a rabi season crop. It is an important oilseed crop grown in diverse agro-climatic conditions ranging from north-eastern to north-western hills and southern Indian states under irrigated/rainfed, timely/late-sown conditions (Fagodiya et al., 2024). Mustard genetic improvement program was initiated at BARC with an objective to identify mutants possessing higher seed and oil yield, thinner seed coat and low fibre content. With sustained efforts in breeding for these traits, BARC has successfully developed nine improved varieties (Table 1; Fig: 3) for farmer's cultivation. A beta ray from the P-32 radioisotope was used to develop a yellow seed coat mutant variety, TM-2. Its recurrent irradiated mutant was later developed as TPM-1 with reduced erucic acid (25%). The saga later continued with several other varieties such as TM-4, TBM-204, TAM108-1, THPM-1, BBM-1, and TBM-143 released for Assam, Maharashtra, West Bengal, Himachal Pradesh, and Jharkhand states. Most of these mutant varieties possessed more grain and oil yields, altered seed coat colour and tolerance to pests and diseases. TAM108-1 mustard variety has become a popular variety in Vidarbha and presently covers 30% of the mustard-growing fields in this region. Recently, 'Trombay Jodhpur Mustard 2 (TJM 2)' was released for the state of Rajasthan, which showed 14% yield superiority over the existing varieties with 40% oil content and resistance to powdery mildew and white rust.

6.1.3. Soybean

Soybean (*Glycine max* (L.) Merr.) is a leading oilseed crop cultivated globally for food, feed and industrial products. Soybean serves as an important source for protein and oil representing more than 60% of global vegetable oil and protein consumption. The yield potential of this crop is often challenged by the growth-limiting factors, mainly soil moisture and terminal heat stress at critical growth stages, and susceptibility to viral/fungal diseases (Mishra et al., 2024). In order to breed for high-yielding varieties with enhanced oil and protein qualities and tolerance to bacterial pustule diseases, BARC has developed two soybean varieties viz., TAMS-38 and TAMS-98-21 through gamma ray irradiation and recombination breeding methods, respectively (Table: 1). Both varieties, recommended for the Vidharbha regions of Maharashtra, are non-pod shattering, tolerant to pests and diseases.

6.1.4. Linseed

Linseed (*Linum usitatissimum* L.) is a traditional oilseed crop and a rich source of ω–3 fatty acids and high-quality protein. It's a cool-season crop and adapted to poor soils/management practices. Due to its high economic value relative to the high quality of the seed oil, it is being increasingly used by consumers, the food and the cosmetics and eco-materials industries (Langyan, et al., 2023). The oil profile is mainly dominated by unsaturated fatty acids, especially, linolenic acid (36-50%), linoleic acid (18-24%), and oleic acid (16-24%). In order to enable linseed oil for edible purposes, BARC has developed TL-99 variety with 2-5% linolenic acid and better seed yield compared to the existing varieties (Table: 1). It is recommended for cultivation across Assam, Bihar, Jharkhand, Nagaland, Uttar Pradesh and West Bengal.

6.1.4. Sesame

Sesame (*Sesamum indicum* L.) is a valuable oilseed crop known for its high oil quality, protein, antioxidant content, and wide adaptability in extreme climatic and edaphic conditions. The main breeding objectives are to improve seed and oil yield, seed size, better plant type, tolerance to biotic and abiotic stresses and indehiscent capsules. Recently, the Trombay Latur Til-10 (TLT-10) sesame variety has been developed and released in collaboration with Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani possessing bold seeds and better seed yield (about 20%) compared to the existing varieties (Table: 1).

6.1.5. Sunflower

Sunflower (*Helianthus annuus*L.) is the world’s third most important source of vegetable oil due to its high concentration of polyunsaturated fatty acids and protein content. In order to breed for high-yield, a gamma ray induced black seed coat mutant, TAS-82 was released for the Maharashtra state.

6.2. Pulse crops

India is the world's largest producer, importer and consumer of pulses, with an area of over 35 million hectares and production of 27.30 million metric tons. They are the rich source of protein (20-25%) and supplements dietary requirement of >40% of the human population and 2/3 of the livestock (Sah et al., 2024). Pulses are attracting attention from the government’s initiative to double farmer’s revenue by diversifying production from traditional cereal-based crops (Souframanian and Dhanasekar, 2023). Due to their high agricultural value, extensive research has been carried out on pulse crops through conventional, mutation and molecular breeding resulting in the development of several high-yielding varieties. Factors like cultivation in risk-prone environments, erratic rainfall, prolonged dry spells and vulnerability to a variety of pests and diseases are limiting their production.

In order to improve the productivity and tolerance to major diseases, BARC has initiated a mutation breeding program in pulse crops using diverse sources of radiations such as gamma rays and electron beams. So far, BARC has developed 24 high-yielding varieties in mungbean, urdbean, pigeonpea, and cowpea, which are either direct mutants or mutant derived varieties (Table: 2). In mungbean, TAP-7 was the first mutant variety released for the Karnataka and Maharashtra regions, having early maturity and tolerance to powdery mildew disease. This was followed by a series of varieties viz., TARM-1, 2& 18, TMB-37, TJM-3, TM-96-2, 2000-2 and recently TRCRM-147 released for various Indian states (Fig: 4). Most of these varieties were known for their bold seed, early maturity, and tolerance to powdery mildew, yellow mosaic and *Rhizoctonia* root rot diseases (Dhole et al., 2024).

Fig: 4 Major Trombay pulse crop varieties released for farmer's cultivation

Among the Urdbean varieties, TAU-1, 2 and TPU-4 were initially developed by cross-hybridization of large seed mutants. Later, TU-94-2, TU-40, TJU-130, TJU-339, and TRCRU-22 were released for Andhra Pradesh, Karnataka, Madhya Pradesh and Tamil Nadu states (Fig: 4). The key traits modified were resistance to powdery mildew, yellow mosaic virus and anthracnose diseases.

The pigeon pea mutant, TT-6, was developed for early maturity and large seeds and later four more varieties were developed. Notably, TT-401, TJT-501, and PKV Tara were developed by crossing a fast neutron-induced large seed mutant and an early maturity genotype (Fig: 4). They were known to possess early maturity, resistance to *Fusarium* wilt, sterility mosaic and *Phytophthora* blight diseases.

A cowpea variety, TC-901 was developed for summer cultivation in Gujarat, MP, Rajasthan, Uttarakhand and West Bengal states (Fig: 4). It is known for earliness, synchronous maturity, tolerance to yellow mosaic and root rot diseases. In addition, TRC-77 (Kalleshwari) was a medium-large seed developed as dual-purpose variety for rice fallows of Chhattisgarh.

Most of these pulse varieties were highly popular among the farmers due to their enhanced yield and resistance to multiple diseases. Among them, TAU-1 has covered more than 50% of urdbean cultivable area in Maharashtra and TU-40 is highly popular among the southern states. TMB-37 of mungbean is also popular in the north-eastern and Punjab states for its large seed and tolerance to yellow mosaic disease. In the central India, Maharashtra farmers are getting better yield by cultivating the pigeon pea variety, PKV Tara, especially under the drip irrigation system. The recently released pulse varieties, TC-901 (cowpea), TRCRM-147 (mungbean), and TRCRU22, TJU339, and TJU-130 (urdbean) are becoming popular in combating yellow mosaic disease. These Trombay mutant pulse varieties are improving the farmers income and boosting the productivity and nutritional security of the country.

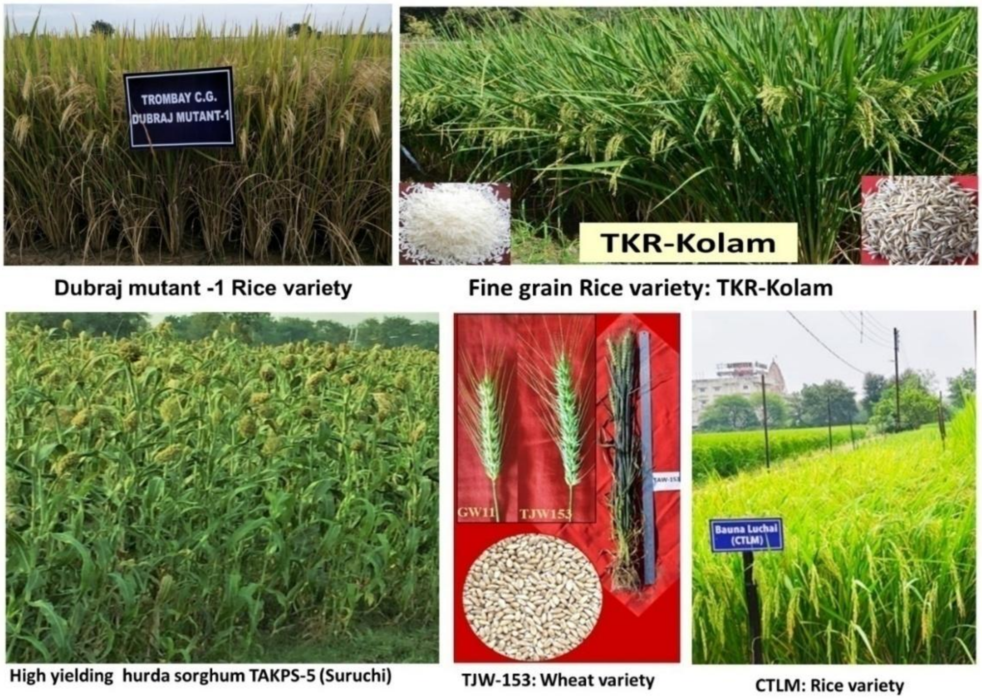

Fig: 5 Major Trombay cereal crop varieties released for farmer's cultivation

6.3. Cereal crops

6.3.1. Rice

Rice (*Oryza sativa* L.) is one of the oldest and most important staple crop for more than 50% of the global population. The increasing frequency of temperature extremes, the onset of drought, storms, floods and pest/diseases are the major production constraints. Therefore, it is essential to develop high-yielding, climate-resilient and nutritionally improved rice varieties. In this context, BARC has developed ten rice varieties suitable for various cropping systems and consumer needs (Table:3). Among them, nine gamma-ray-induced mutants have been released for Chhattisgarh and Andhra Pradesh and a mutant derivative for Maharashtra state. Most of them were improved for higher grain yield, long-slender grain type, semi-dwarf, lodging tolerance and grain qualities. Notably, TCSM, TCVM, and CGIT were gamma-ray-induced mutants with improved grain yield, semi-dwarfness, and resistance to lodging and shattering. They were developed in collaboration with Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh. Recently, Chhattisgarh TrombayLuchai Mutant-CTLM had been released for early maturity, lodging resistance, higher grain yield, and cooking quality (Fig: 5). While, Sanjeevani, a pureline selection from Lycha landrace from Chhattisgarh containing more than 350 phytochemicals known for therapeutic and medicinal properties, boosting immunity and antioxidant responses has been released for Chhattisgarh. In addition, Trombay Konkan Khara was specifically bred for Maharashtra's saline coastal soils in collaboration with Dr.Balasaheb Sawant Konkan Krishi

Vidyapeeth, Dapoli. It showed 15% higher grain yield than its parent under saline conditions, making its cultivation possible in brackish soils.

6.3.2. Wheat

Bread wheat (*Triticum aestivum* L.) is cultivated across the world as a major cereal crop and accounts for 20% of the calories and proteins in the human diet. The majority of global wheat production occurs under rainfed conditions and such cropping systems are subject to terminal heat and droughts due to insufficient and/or poorly distributed precipitation. Rapidly changing climatic conditions, particularly the prevalence of higher temperatures during the grain-filling stage, negatively impact the production (Rana et al., 2024). In order to breed for such conditions, BARC has developed two varieties, viz., Trombay Jodhpur Wheat-153 (TJW-153) in collaboration with the Jodhpur Agricultural University for arid conditions of Rajasthan and Trombay Raj Vijay Wheat (TRVW-155), developed in collaboration with Rajmata VijayarajeScindia Krishi Vishwavidyalaya, Gwalior for Madhya Pradesh (Table: 3; Fig: 5).They possess tolerance to early and terminal heat stress, blast and powdery mildew diseases and enhanced zinc & iron contents.

6.3.3. Sorghum

Sorghum (*Sorghum bicolor* L.) is a major cereal crop grown worldwide for its grain, livestock feed and biofuel. It has wide adaptability to a range of soil types, climatic conditions, and environmental stresses. Under the changing climate scenario, there has been a drastic reduction in the area and production due to the delayed onset of early rains, increased pests and diseases and depleting residual soil moisture during maturity (Somu et al., 2024). Since economically important traits are quantitative in nature with low heritability, there is a need for improving genetic variability for these traits using mutation breeding methods. In this direction, BARC started genetic improvement program in rabi sorghum and successfully developed two gamma ray mutants viz., TRJP 1-5 and TAKPS-5, in collaboration with the University of Agricultural Sciences, Raichur, and Dr. PDKV, Akola respectively (Table: 3; Fig: 5). TRJP 1-5: a rabi cultivated mutant released for N-Karnataka region, showed improved grain yield, synchronous maturity, bold and lustrous seeds, better rheological properties (roti making), and moderate tolerance to charcoal rot, rust, and blight diseases. In addition, a hurda sorghum mutant, TAKPS 1-5 (Suruchi), was released for the Vidarbha regions of Maharashtra (Ganapathi and Badigannavar, 2020). It is a short-duration hurda variety for the rabi season with improved green hurda yield, more spongy tissues, better flavour and shelf life.

7. Conclusions

Mutation breeding has been instrumental in inducing novel mutations for beneficial traits, supplementing the agriculture productivity and nutritional enhancement of field crops. Successful use of radiation has lead to improvement of grain yield, nutritional quality and wider adaptability of the field crops, such as cereals, pulses, millets, and oilseeds. Integrating mutation breeding with the next-generation sequencing (NGS) technologies will result in the development of extensive molecular resources, enabling trait mapping and marker-assisted breeding in faster and more reliable way. In this direction, developments in the radiation induced mutation breeding will help in understanding functional/regulatory roles of the economically important quantitative traits.

Acknowledgements

The authors would like to thank all the concerned breeders and supporting staff of the NABTD, BARC for their valuable contribution in the development of mutant varieties. In addition, the efforts of the state agriculture universities and ICAR institutes are highly acknowledged.

Table: 1 List of Trombay oilseed varieties released for farmer's cultivation

Crop	Variety	Year of release	Recommended States	Salient features
Groundnut	CGTM (TG-88)	2024	Chhattisgarh	High oleic content, recommended for both rainy and summer seasons
	GG-37	2023	Gujarat	Higher pod yield, better shelling out turn, stay-green at harvest, summer suitable, more 3-seeded smooth pods
	TAG-73	2021	Maharashtra	Higher pod yield, better shelling out turn, stay-green at harvest, summer suitable, more 3-seeded smooth pods
	TG-47 (RARS T1)	2011	Andhra Pradesh	Large seed, 115 days maturity, more 3-seeded pods
	TDG-39 TBG-39	2009 2008	Karnataka Rajasthan	Large seed, medium maturity, high oleic acid, more branches
	TG-51	2008	West Bengal, Odisha, Bihar, North Eastern States	Early maturity, high shelling per cent, Medium-large seed, Suitable for rice fallows
	TLG-45	2007	Maharashtra	Large seed, medium maturity
	TG-38	2006	West Bengal, Odisha, North Eastern States	High shelling per cent, more 3-seeded pods, stem rot tolerance
	TG-37A	2004	Rajasthan, Uttar Pradesh, Punjab, Haryana, Gujarat, West Bengal, Odisha, North-Eastern States	High yield, collar rot and drought tolerance
	TPG-41	2004	All India	Large seed, medium maturity, high oleic acid
	TG-26	1996	Gujarat, Madhya Pradesh, Maharashtra	Earliness, high harvest index, 20 days seed dormancy
	TKG-19A	1996	Maharashtra	Large seed, 30 days seed dormancy
	TG-22	1992	Bihar	Medium large seed, 50 days seed dormancy
	TAG-24	1992	Maharashtra, Rajasthan, Karnataka, Odisha, West Bengal	Earliness, high yield, high harvest index, high percent partitioning , Semi dwarf, Wider adaptability
	Somnath (TGS-1)	1991	Gujarat	Large seed, semi-runner type
	TG-3	1987	Kerala	High yield
	TG-17	1985	Maharashtra	No secondary branches, 30 days seed dormancy
	TG-1	1973	Maharashtra, Gujarat	High yield, large seed, more branches, 50 days seed dormancy
Soybean	TAMS 98-21	2007	Maharashtra	High yielding, resistant to bacterial pustules, *Myrothecium* leaf spot and soybean mosaic virus diseases
	TAMS-38	2005	Maharashtra	Early maturing, resistant to bacterial pustule and *Myrothecium* leaf spot

Mustard	TJM-2	2024	Rajasthan	Higher seed and oil yield, resistance to powdery mildew and white rust
	TBM-143	2022	West Bengal	Appressed pods, yellow seeds, resistance to lodging and shattering
	THPM-1	2021	Himachal Pradesh	High yield, semi-erect to erect plant, long main fruiting axis
	BBM-1	2021	Jharkhand	High yield,bold seed, drought tolerant, long main fruiting axis
	TAM-108-1	2021	Maharashtra	High yield, bold seed, more siliqua density
	TBM-204	2019	West Bengal	Yellow seed, high yield, dark green leaves, prominent constriction on siliqua
	TPM-1	2007	Maharashtra	Yellow seed, powdery mildew tolerant, early, high yield
	TM-2	1987	Assam	Appressed pod, high yield
	TM-4	1987	Assam	Yellow seed, high yield
Sunflower	TAS-82	2007	Maharashtra	Black seed coat, tolerant to drought
Sesame	TLT-10	2024	Maharashtra	Bold seeded, higher seed yield
Linseed	TL-99	2019	Uttar Pradesh, Bihar, Jharkhand, West Bengal, Assam, Nagaland	Low linolenic acid, high yield and oil content
Jute	TKJ-40 (Mahadev)	1983	Odisha	High yielding

Table: 2 List of Trombay pulse varieties released for farmer's cultivation

Crop	Variety	Year of release	Recommended States	Salient features
Mungbean	TRCRM-147	2023	Karnataka	Suitable for summer, resistant to yellow mosaic disease, large seed size, High yield
	TM-2000-2 (Pairy Mung)	2010	Chhattisgarh	Suitable for rice fallow and resistant to powdery mildew
	TM-96-2 (Trombay Pesara)	2007	Andhra Pradesh	Resistant to powdery mildew and Corynespora leaf spot
	TJM-3	2007	Madhya Pradesh	Resistant to powdery mildew, yellow mosaic virus and Rhizoctonia root-rot diseases
	TMB-37	2005	Uttar Pradesh, Bihar, Jharkhand, Assam, West Bengal	Tolerant to yellow mosaic virus
	TARM-18	1997	Maharashtra	Resistant to powdery mildew
	TARM-1	1997	Maharashtra, Gujarat, Madhya Pradesh, Andhra Pradesh,Telangana, Kerala,TamilNadu, Odisha, Karnataka	Resistant to powdery mildew
	TARM-2	1994	Maharashtra	Resistant to powdery mildew
	TAP7	1983	Maharashtra, Karnataka	Tolerant to powdery mildew
Blackgram	TJU-130	2023	Madhya Pradesh	Resistant to YMD, anthracnose & powdery mildew
	TJU-339	2023	Madhya Pradesh	Resistant to YMD, anthracnose & powdery mildew

	TRCRU-22	2023	Karnataka	Suitable for summer, YMD resistant, medium large seeds, high yield
	TU-40	2013	Andhra Pradesh, Karnataka, Odisha, TN	Suitable for rice fallows and resistant to powdery mildew
	TU 94-2	1999	AP, Kerala, Karnataka, Tamil Nadu	Resistant to yellow mosaic virus
	TAU-2	1993	Maharashtra	High yielding
	TPU-4	1992	Maharashtra, Madhya Pradesh	Large seed
	TAU-1	1985	Maharashtra	Large seed, most popular variety in Maharashtra
Pigeonpea	PKV-TARA	2013	Maharashtra	Resistant to wilt and sterility mosaic
	TJT-501	2009	Madhya Pradesh, Maharashtra, Gujarat, Chhattisgarh	High yielding, tolerant to Phytophthora blight, early maturing
	TT-401	2007	Madhya Pradesh, Maharashtra, Gujarat, Chhattisgarh	High yielding, tolerant to pod borer and pod fly damage
	TAT-10	1985	Maharashtra	Early maturing
	TT-6	1985	Madhya Pradesh, Kerala Maharashtra, Andhra Pradesh, Gujarat, Karnataka,	Large seed
Cowpea	TC-901	2018	Gujarat, Rajasthan, Madhya Pradesh, West Bengal, Maharashtra, Uttarakhand	Suitable for summer, mosaic and root rot resistant, early and synchronous maturing
	TRC-77-4 (Khalleshwari)	2007	Chhattisgarh	Suitable for rice based cropping system

Table: 3 List of Trombay cereal varieties released for farmer’s cultivation

Crop	Variety	Year of release	Recommended States	Salient features
Rice	BaunaLuchai-CTLM	2024	Chhattisgarh	Dwarf, early maturing, lodging resistance, soft cooked quality and high yield
	Sanjeevani	2024	Chhattisgarh	Therapeutic and medicinal property, boost immunity and antioxidant responses
	Trombay Konkan Khara	2024	Maharashtra	Higher yields in saline soils, suitable for non-arable brackish water
	TCVM	2021	Chhattisgarh	High yielding, Semi-dwarf, medium duration, lodging resistant & highly aromatic
	TCSM	2021	Chhattisgarh	Semi-dwarf, high yielding (60-65 q/ha), late maturing
	CGJT	2021	Chhattisgarh	Short slender, aromatic, semi-tall, lodging resistant
	Vikram-TCR	2021	Chhattisgarh	Semi-dwarf, lodging resistant, drought tolerant
	TKR-Kolam	2020	Maharashtra (Konkan)	Semi-dwarf, very fine grain, high yielding
	TCDM-1	2019	Chhattisgarh	Semi-dwarf, lodging resistant, highly aromatic
	Hari	1988	Andhra Pradesh	Slender grain type

Sorghum	TAKPS-5	2023	Maharashtra	Better hurda yield, early maturing, compact panicles, sweet grains
	TRJP1-5	2023	Karnataka	Synchronized flowering, large seeds, good roti making quality, medium duration
Wheat	TJW-153	2024	Rajasthan	Heat tolerant, resistant to fungal diseases like blast and powdery mildew.
	TRVW-155	2024	Madhya Pradesh	Enhanced iron and zinc content, better chapatti making quality, resistant to fungal diseases like rust, bunt and powdery mildew.

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Potential of Nuclear Analytical Techniques for Industrial and Societal Applications

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***Abstract**:* Chemical characterization of a material of interest is the first and most important step in chemical quality control (CQC) exercise. It involves quantification of total elemental and/or isotopic concentrations at major to trace levels by suitable analytical technique(s) with good accuracy and precision. Compared to various conventional analytical techniques, neutron and proton based Nuclear Analytical Techniques (NATs) like Neutron Activation Analysis (NAA), Prompt Gamma-ray NAA (PGNAA) and Ion Beam Analysis (IBA) techniques like Particle Induced Gamma-ray (PIGE) are unique due to their advantageous analytical properties like non-destructive analysis of solid or as received samples, simultaneous multielement capability from major to trace concentration levels, quantitative information on total elemental concentration along with isotopic or chemical species for specific elements, negligible or less matrix effects and spectral interference. Since 1994, Radiochemistry Division, BARC is engaged in developing k_0-based conventional and Internal Mono-standard Neutron Activation Analysis (k_0-NAA & IM-NAA) and Prompt Gamma-ray NAA (PGNAA) methods utilizing neutron flux/beam from research reactors (Dhruva and Apsara-U) at BARC for analysis of small and large size samples for determination of H to U as well as in situ, internal and external current normalized Particle Induced Gamma-ray Emission (PIGE) method utilizing low energy (2-5 MeV) proton beam from Folded Tandem Ion Accelerator (FOTIA) for low Z elements. These methods have been applied to various fields like nuclear technology, materials science, geology, environment, biology, food & agriculture, archaeology and forensic science having important industrial and societal applications. IM-NAA using in situ detection efficiency was successfully employed for standard-less compositional characterization of large size reactor structural materials like zircaloys, stainless steels, Ni-based alloys for CQC, impurities in high purity materials like 1S-Al and nuclear grade graphite as well as archaeological clay potteries for provenance studies. PGNAA method was utilized for non-destructive analysis of samples like various alloys, cement and glass as well as for total Boron and ^{10}B content in boron-based ceramics. PIGE methods were utilized for simultaneous quantification of low Z elements namely Si, B, Al, Na, Li and F in Ba-borosilicate glass, Li & Ti in lithium titanate and total B and its isotopic composition (IC) ($^{10}B/^{11}B$ atom ratio) in boron-based ceramic/refractory neutron absorbers including B_4C. External (in air) PIGE facility at FOTIA developed using thin tantalum window enabled rapid analysis of “as received” samples of glass, ceramics and alloys as well as liquids (water) for low Z elements and IC of Boron in B_4C for commercial usage to certify B-10 isotope content in industrial samples relevant for Indian power reactors. Recently, INAA and PIGE methods were utilized for forensic studies of real-case automobile (car) windshield glass samples under an IAEA CRP as well as for quality assessment of food samples and examining quality of coal through ash content and cement via Ca/Si concentration value.

1. Neutron Activation Analysis (NAA)

George de Hevesy and Hilde Levi first introduced the NAA technique in 1936, by using (alpha, n) neutron source. NAA method is being widely used for multi-elemental determination in a variety of matrices like geological, biological, environmental, archaeological, precious materials (gemstones), high purity materials and nuclear reactor structural materials. The high sensitivity of this technique is because of irradiation of samples at high neutron flux available from the research reactors and measurement of gamma rays from the samples using high-resolution high purity Germanium (HPGe) detector coupled to multichannel analyser (MCA). The technique provides a possibility to perform analysis non-destructively (solid powder or as received sample, without chemical dissolution) using instrumental neutron activation analysis (INAA). Many elements from Na to U including transition elements and rare earth elements (REEs) are routinely determined by NAA methods.

1.2. Principle of Prompt Gamma-ray Neutron Activation Analysis (PGNAA) & NAA

When a target isotope of an element is exposed to neutrons, a compound nucleus (CN) is formed in the excited state. The CN decays to lower energy ground state by emitting gamma rays promptly (10^{-12} to 10^{-13} s) which is called prompt γ-rays and intensity of these γ-rays is directly proportional to isotopic (elemental) concentrations. This on-line measurement technique is called prompt gamma-ray NAA (PGNAA). The CN in the ground state decays often by emitting a β^- particle and the product formed is an isotope of another element that de-excites to ground state by emitting characteristic (delayed) gamma rays. In conventional NAA, intensity of these γ-rays is measured. PGNAA and NAA are schematically represented in **Fig. 1.** The activity produced in NAA at the end of irradiation period (t_i) is given by,

$A = N \sigma \phi (1-e^{-\lambda t_i})$

N is the number of target atoms, σ is the (n,γ) capture cross section in barn (cm^2), ϕ is the neutron flux ($cm^{-2} s^{-1}$) and λ is the decay constant (s^{-1}) of the activation product. Elemental concentration is calculated by relative method or k_0-based (single comparator) method.

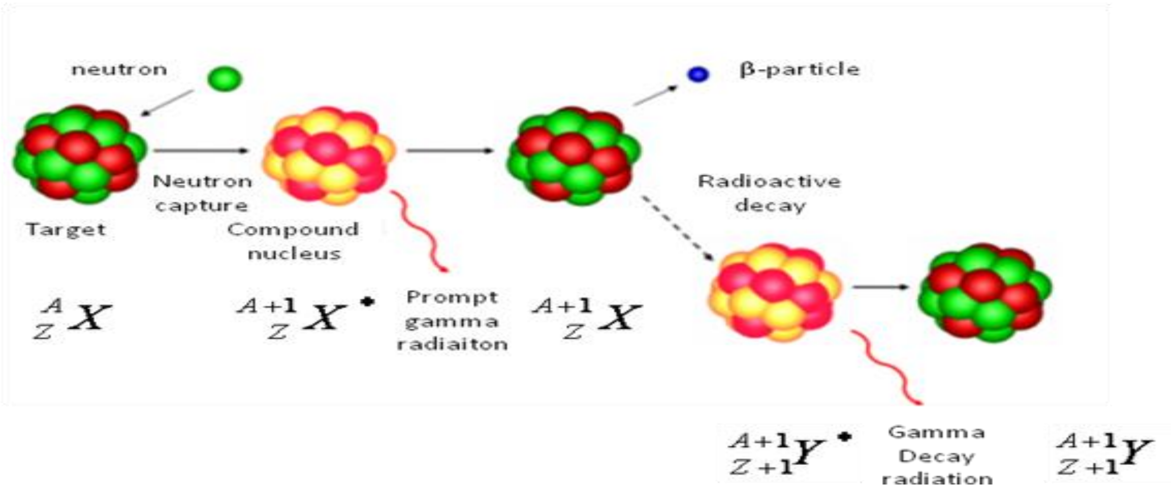


Figure 1. Interaction of neutrons with target isotope and production of prompt and delayed gamma rays (Source : The schematic figure is taken from literature of Institute of Isotopes, presently Centre for Energy, HAS, Budapest)

1.3. Concentration Calculation: Relative vs. Single Comparator or k_0- based method

Relative or comparator method is mostly used by users and this is a simple approach where in sample in corradiated with single or multi-element standard (or in some cases a matrix match RM or CRM) along with a control sample (CRM or SRM). Elemental concentration (absolute concentration (m) is calculated from count rate (cps) using following formula.

$$m_{sample} = m_{std} \times \frac{cps_{sample}}{cps_{std}} \times \frac{\left[e^{-\lambda t_d}\right]_{std}}{\left[e^{-\lambda t_d}\right]_{sample}}$$

The absolute concentration (m) is converted to concentration value in ppm (mg kg^{-1}) or percentage by dividing samples mass. The single comparator method, later modified to k_0-based NAA method is attractive as it does not need elemental standard for each element. This method is based on the co-irradiation of the sample with a single comparator like Au or any other suitable element, and the use of literature available experimentally determined composite nuclear constant k_0. The k0-factor is theoretically represented as the ratio of four nuclear constants wrt. Au as given below:

$$k_0 = \frac{M_{Au}\theta\sigma_0 a_\gamma}{M\theta_{Au}\sigma_{0(Au)}a_{\gamma(Au)}}$$

The analysis results are linked to the k_0 factors, absolute detection efficiency and neutron spectrum characteristics (f & α) . The concentration of an element is calculated using the following equation.

$$C\,(mg/kg) = \frac{\frac{PA/LT}{SDCW}}{(PA/LT)/SDCm)_{Au}} \times \frac{1}{k_0} \times \frac{[f + Q_0(\alpha)]_{Au}}{[f + Q_0(\alpha)]} \times \frac{\epsilon_{Au}}{\epsilon}$$

where N_p is the net counts, W and m are masses of sample and single comparator respectively, $Q_0(\alpha)$ (=$I_0(\alpha)$ /σ_0) is the α corrected Q_0 and the k_0 is a factor and is taken from the literature. The reactor-based parameters (f and α*)* are pre-determined for the irradiation position used for standardization purposes. The symbol "*" refers to the comparator element. Recently, the k_0-NAA method has been standardized by characterizing the G4 irradiation position of the upgraded Apsara (**Apsara-U**) reactor (**Fig 2**). The sub-cadmium to epithermal neutron flux ratio (*f*) and epithermal neutron flux shape factor (α) were determined taking dual and multi flux monitors using Cadmium ratio method. The value of *f* at G4 position was found to be **19.94 ± 1.02** with average value of α as **-0.027 ± 0.003** indicating hard neutron spectrum[1].

1.4. The k_0-based internal monostandard NAA (IM-NAA) method

The Internal Monostandard NAA (IM-NAA) is promising for analysing large and non-standard geometry samples including small size samples. This method utilizes an element present in the sample as monostandard and *in situ* relative efficiency by using gamma lines of activation products produced in each sample. The *in-situ* detection efficiency takes care of attenuation and geometrical effects of sample, and thus makes the method geometry independent. This approach gives elemental concentration of an element (x) relative to mono standard (y) as given below,

$$\frac{m_x}{m_y} = \frac{\left[(S.D.C).\left(f + Q_0(\alpha)\right)\right]_y}{\left[(S.D.C).\left(f + Q_0(\alpha)\right)\right]_x} \cdot \frac{PA_x}{PA_y} \cdot \frac{\epsilon(y)}{\epsilon(x)} \cdot \frac{1}{k_0}$$

where $k_0 = k_{0,Au}(x) / k_{0,Au}(y)$ and obtain terms are already defined. The relative concentrations are converted to absolute value by using mono-standard mass obtained by any other method or NAA using a sub-sample analysis. In special cases like metals and alloys, where all the major and minor elements are amenable to NAA, absolute concentrations can be arrived using mass balance[2].

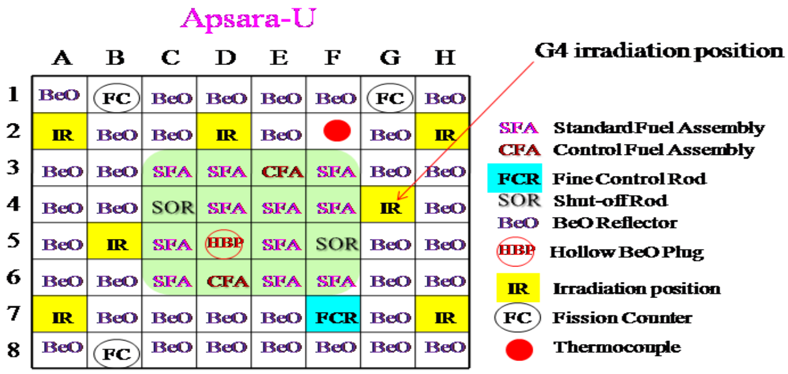


Figure 2. Sample Irradiation Position in Apsara-U research reactor (Ref: 1, Samanta et al]

1.5. Prompt Gamma NAA (PGNAA) utilizing thermal neutron beam from Dhruva research reactor

When a thermal neutron is captured by the target nuclide, it is formed with excitation energy of about 2-8 MeV, depending on the binding energy of neutron. During the process of de-excitation of these nuclei, gamma-rays characteristic of the nuclide is emitted and are called prompt gamma rays. These gamma-rays are used for qualitative and quantitative assay of the target nuclei and technique based on this is called Prompt Gamma-ray Neutron Activation Analysis (PGNAA). The PGNAA is emerging as an attractive technique for the concentration determination of elements in varieties of samples. The PGNAA method is complementary to conventional NAA and is suitable for most of the elements including low Z elements such as H, B, Si, P, S, Cl and Ti. The prompt gamma ray method is particularly useful for elements where product nucleus during normal NAA may have any of these difficulties, like (i) too short a half-life, (ii) too long a half-life, (iii) a stable nuclide like $^{12}C(n,\gamma)^{13}C$ and $^{10}B(n,\gamma)^{11}B$, (iv) a target nuclide having low isotopic abundance and (v) no delayed gamma ray from activation product like ^{32}P and ^{35}S. Non-destructive analysis of samples can easily be done by PGNAA, as the residual activity formed by irradiation of sample is less (due to low neutron flux about 10^{5-7} $ncm^{-2}s^{-1}$) and total counts depends on duration of assay / counting during irradiation. High neutron absorption cross section elements like B, Cd and Gd and major elements of samples of various matrices including alloys can easily be done by PGNAA[3]. A s there is no saturation factor, at same flux (needs a flux normalizer element like Cl or H etc), the concentration calculation is simple by relative method as given below.

$$m_{sample} = m_{std} \times \frac{cps_{sample}}{cps_{std}}$$

In IM-PGNAA, the calculation of concentration is simple, as there is no f and α components, since thermal neutron beam or more than 99.95 % (thermal neutron component) is used.

$$\frac{m_x}{m_y} = \frac{P_{Ax}}{P_{Ay}} \cdot \frac{\varepsilon_y}{\varepsilon_x} \cdot \frac{k_{0,H}(y)}{k_{0,H}(x)}$$

1.5.1. Facilities for NAA and PGNAA

Neutron irradiation facilities currently available at BARC, Trombay include Dhruva reactor, Apsara-U reactor and Critical facility reactor. Some of the neutron irradiation facilities utilized for NAA work are given in Fig. 3. The Pneumatic Carrier Facility (PCF) of Dhruva reactor is utilized during neutron irradiation of samples for R&D work and routine sample analysis using NAA. PCF is useful for those elements namely Al, V, Ti, Mg, Ca, Mn, Na, K and a few REEs whose activation products are short and medium lived (half-lives in the ranges of minutes to hours). The turnaround time of analysis is less as it involves short irradiation and faster counting of irradiated samples. The available neutron fluxes from thermal column to core irradiation positions of research reactors at BARC are in the range of 10^7-10^{14} n cm^{-2} s^{-1}.

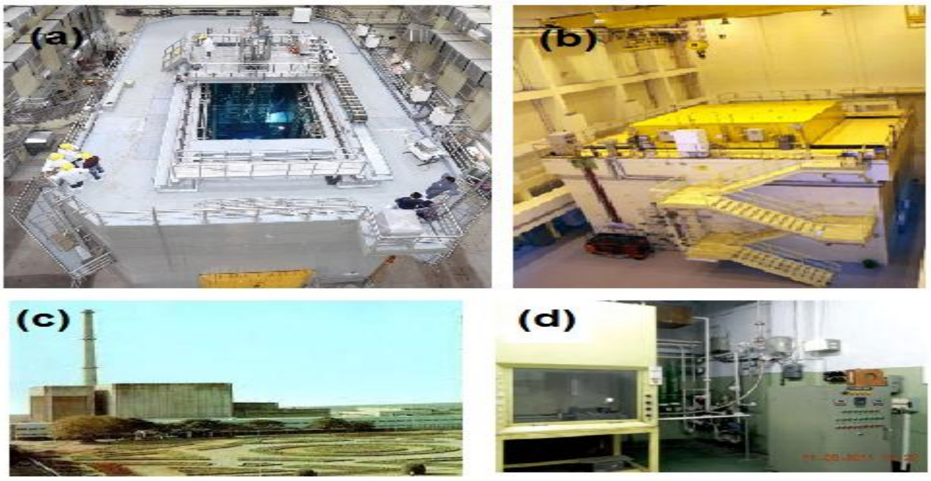


Figure 3. Facilities for neutron irradiations (a) Apsara-U reactor, (b) Critical facility (CF) reactor, (c) Dhruva reactor, (d) Pneumatic Carrier facility (PCF) at Dhruva reactor, BARC

HPGe detector coupled to MCA is widely used during conventional NAA and PGNAA due to better resolution and also better efficiency in some cases. For Compton suppressed detection system: HPGe-BGO or HPGe-NaI(Tl) is suitable in anti-coincidence mode (Fig 4).

A Prompt Gamma-ray Neutron Activation Analysis (PGNAA) facility was set up using thermal neutron beam at Dhruva research reactor. It was utilized for non-destructive quantification of total boron by measuring 478 keV prompt gamma-ray from $^{10}B(n,\alpha)^{*7}Li$ reaction in different boron based ceramic and refractory neutron absorbers having natural as well as enriched boron composition. Self-shielding correction was carried out for higher boron concentration samples using Cl as internal standard[3]. Further, BARC (RCD) is working to have a dedicated PGNAA facility at Apsara-U for departmental work program as well as research work.

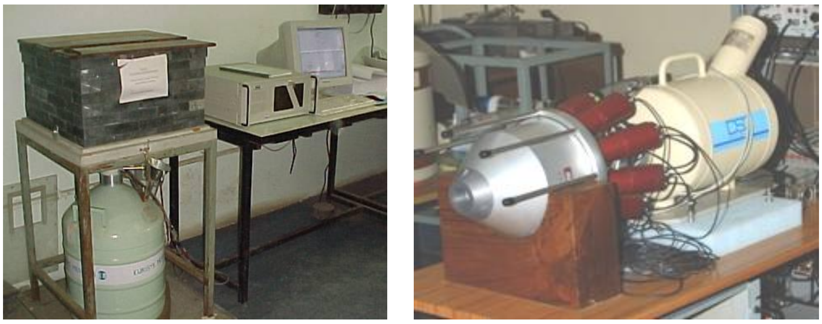


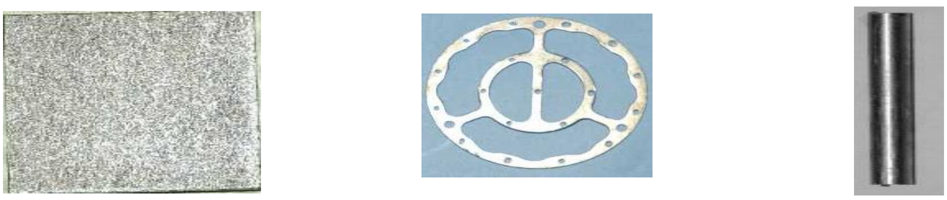
Figure 4. Typical gamma-ray spectrometry setup (a) singles counting using HPGe detector coupled to MCA and (b) Compton Suppressed system using HPGe-BGO detectors for NAA & PGNAA

1.6. Applications of IMNAA and PGNAA

Compositional characterization and trace element determination in materials developed or procured or synthesized is very important under chemical quality control (CQC) exercise for their acceptance in the intended use. Compositional characterization was carried out in various alloys having nuclear and non-nuclear applications. NAA/ IM-NAA methods were developed and utilized for the determination of elements (impurities) in high pure materials. The IM-INAA in conjunction with in situ detection efficiency is useful for the analysis of metals and alloys of irregular size samples (Fig. 5) like zircaloy-2, Zirclaoy-4, and stainless steel (SS-316M). Samples were irradiated in the thermal column (for large size) as well as in the core position (for small size) of the Apsara reactor. The corresponding neutron fluxes are about $2\text{x}10^{8}$ $cm^{-2}s^{-1}$ and $5\text{x}10^{11}$ $cm^{-2}s^{-1}$ respectively. Zr and Fe present in the samples were used as internal monostandard in zircaloys and stainless steels, respectively. In addition to major and minor elements in zircaloys and stainless steels, some trace elements like As, Co, Sn, Ta and W were quantified. In the presence of major element of Zr, trace Hf could be determined in Zirclaoy-2 sample. Since all the major and minor elements in zircaloys and stainless steels are measurable by NAA, concentrations were obtained by a standard-less approach (mass balance procedure) by using IM-NAA method[4].

1.6.1. Application of INAA or IM-NAA to archaeology for provenance study of ancient pottery samples

*S*everal pottery samples collected from different excavated Buddhist sites of India were analysed by IM-NAA. Concentrations of 20 elements consisting of Al, alkali, alkaline and transition elements were determined in pottery as well as soil samples from the same location. Elemental concentration ratios of Al to Sc and concentrations of some key elements namely Na, K, Rb, Cs and Ba as well as Sc, Fe, Co, Cr, Hf and Mn were used to establish the provenance/grouping of pottery artifacts, i.e., whether they belong to same of different sources/origin. REEs in these pottery samples were determined and their concentrations were used for grouping. Provenance / grouping studies could be carried out by a standard-less approach using elemental concentration ratios with respect to Sc (normalizing element) using IM-NAA, instead of absolute concentrations [5,6].



Zircaloy-2 Zircaloy-4 SS – 316M

Figure 5 .Large and irregular shaped alloy samples analyzed by IM-NAA

Fig. 6: Archaeological (ancient) pottery samples along with a new pottery for LSNAA

1.6.2. Application of INAA using PCF Dhruva for REEs

Determination of Rare Earth Elements (REEs) using spectroscopic methods is challenging. Conventional Instrumental Neutron Activation Analysis (INAA) method utilizing Pneumatic Carrier Facility (PCF) of Dhruva research reactor has been optimized with the short-lived isotopes such as ^{161}Gd, ^{165m}Dy and $^{153/155}Sm$ for quantification of Gd, Dy and Sm respectively. Such isotopes are difficult to observe by conventional INAA with longer cooling periods owing to their very short half-lives (1 – 3 mins). These isotopes are not only observed but also utilized as activation product for rapid determination of these REEs. The standardized method has been utilized for the first time in liquid samples involving nuclear fuel like U_3O_8 wherein TBP/n-dodecane has been applied for chemical separation of Uranium prior to analysis. The INAA method has also been applied for validating the stoichiometry of Gd in Gd^{3+} co-doped $Zn_2P_2O_7:Tb^{3+}$ green emitting solid-state phosphors, which plays a very pivotal role in sensitizing the terbium ion in its performance for solid state lighting[7].

1.6.3. Application of PCF for Uranium estimation in Ores and Minerals

Rapid and non-destructive determination of trace quantities of Uranium in “as received” solid samples using a suitable analytical method is a challenging task. Uranium can be quantified by Instrumental Neutron Activation Analysis (INAA) using both short lived (^{239}U) and medium-lived (^{239}Np from decay of ^{239}U) activation products[8]. In the present work, INAA method has been optimised in terms of sample mass, duration of irradiation, lesser decay period and faster counting to acquire reasonable counts (peak area) under the peak of interest. Pneumatic Carrier Facility (PCF), high neutron flux (5×10^{13} n/cm^2 /s at 50 MW power) at Dhruva research reactor, has been advantageously utilized for short duration irradiation (1 min) of the samples. Quantification of Uranium utilizing ^{239}U short-lived activation product (23.5 min half-life) formed after short irradiation, makes the methodology faster without any longer decay time. Immediately after 1 min of irradiation, the short-lived ^{239}U activation product showed higher analytical sensitivity compared to that of medium-lived activation product (^{239}Np) having gamma-rays at 106 and 277 keV. The detection limit of uranium was found to be much lower when it was calculated using ^{239}U activation product. A comparative study was carried out between the short and medium lived activation products of ^{238}U. The method was applied for determination of trace quantities of total Uranium in ores and minerals like Zircon, Ilmenite and Rutile having complex matrices. The detection limit was found to be around 1 ppb for the analysed solid samples (ores and minerals).

1.6.4. Application of INAA for Glass Forensics

Glass fragments, related to container glass, automobile/windshield glass or window pane glass, are potential forensic evidences in various types of anti-social activities and accidents. INAA is an important technique to get the information on elements of interests from major to trace concentration level. Automobile (windshield/sodalime) glass is mainly composed of elements Si, Na, Ca, Mg and Al at percentage level and transition and rare earth impurities are at trace concentration level. Elements at minor and trace concentration levels are regarded as the key / fingerprinting elements for various glass samples. INAA was utilized for the quantification of fourteen elements including ten trace elements. Elemental concentration rations like La/Ce or La/Sc or total REE are useful for preliminary grouping the similar class of glasses obtained from same or different brands of automobile (e.g., car)[9]. The results of the minor and trace elements (Mn, Sc, Co, Zn, Zr, Ta, Hf, La, Ce, Sm and Eu) present in twenty different automobile glass samples from five different brands could be utilized for grouping the glass samples. Fig. 7 gives INAA application in conjunction with statistical analysis for glass forensics. An IAEA CRP was carried out for glass forensics (car windshield glasses) obtained from Israel utilizing Nuclear Analytical Techniques. Results of trace element about 15 including REEs were used for grouping/provenance study[10-12].

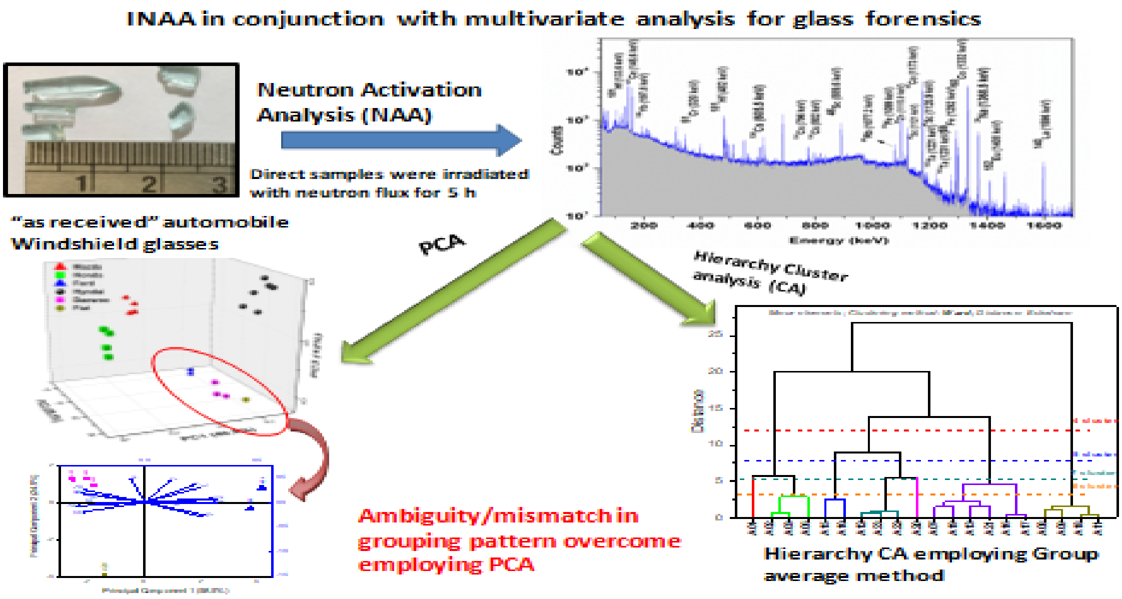


Figure 7. *Glass Forensics steps by INAA and statistical analysis*

2. Ion Beam Analysis (IBA)

IBA techniques like PIGE & PIXE are complementary techniques for low (PIGE) to medium & high Z (PIXE) elements using low energy proton beam from tandem particle accelerators (**Fig 8**). PIGE (Particle Induced Gamma-ray Emission) involves online assay of prompt gamma-rays from isotopes of various elements through inelastic proton beam scattering (p,p'γ) or other nuclear reactions like (p,γ), (p,nγ) and (p,αγ). Commonly used proton induced nuclear reactions of some of the elements are given in the Table 1.

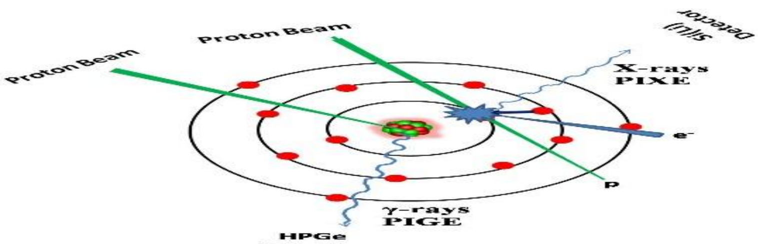


Fig. 8. *Principal of PIGE/PIXE using low energy proton beam*

Table 1. Proton induced reactions of isotopes of low Z elements and prompt gamma-rays of interest in PIGE.

Element	Reaction	Energy (keV)
Li	^{6}Li(p, γ)^{7}Be ^{7}Li(p, p'γ)^{7}Li	429 478
Be	^{7}Be(p, αγ)^{6}Li	3526
B	^{10}B(p, αγ)^{7}Be ^{10}B(p, p'γ)^{10}B ^{11}B(p, p'γ)^{11}B	429 718 2125
C	^{12}C (p, p'γ) ^{12}C	4439
N	^{14}N (p, p'γ) ^{14}N	2313
O	^{16}O (p, p'γ) ^{16}O	6129
F	^{19}F(p, p'γ)^{19}F	110, 197
Na	^{23}Na(p, p'γ)^{23}Na	440
Al	^{27}Al(p, p'γ)^{27}Al	844, 1014
Si	^{28}Si(p, p'γ)^{28}Si	1263, 1779
S	^{32}S(p, p'γ)^{32}S	2230
Ti	^{48}Ti(p, p'γ)^{48}Ti	983

In situ current normalized particle induced gamma ray / X-ray emission (PIGE/PIXE) methods have been standardized by RCD using proton beam from Folded Tandem Ion Accelerator (FOTIA), BARC, 3MV Tandetron at IOP, Bhubaneswar and BARC-TIFR 14 MV Pelletron to determine non-destructively low to medium Z elements glass, ceramics, alloys as well as in geological, environmental, archeological and forensic samples[9-11]. PIGE methods using proton beams from FOTIA were utilized for simultaneous quantification of low Z elements namely Li, B, F, Na, Mg, Si, Al, P & Ti and applied for compositional (low Z element) analysis of borosilicate glass (nuclear waste vitrification matrix), Li & Ti in lithium titanate (a tritium breeder blanket material) and total B and its isotopic composition (IC) (^{10}B/^{11}B atom ratio) in boron-based neutron absorbers. To fulfil the further requirement of simple and rapid analytical method, external (in air) PIGE method has been utilized by us at FOTIA (**Fig 9**)[10-19]. It was found to reduce the turnaround time of analysis without any vacuum requirement, where the sample has been exposed to the extracted proton beam in air. The external PIGE setup has the potential of analyzing "as received" non-standard geometry samples like alloys or archaeological sculptures of non-geometrical size and shape.

Figure 9. Vacuum Chamber and External (in air) PIGE setup at FOTIA, BARC

2.1. Chemical Characterization of sodalime glass using Si as an internal current normalizer in Ext PIGE

Beam current monitoring or normalization is an important aspect in ion beam analysis utilizing particle accelerator for materials characterization. We present an innovative idea of using ^{29}Si, present in the sample, as an internal beam current normalizer for the quantification of low Z elements by particle induced gamma ray emission (PIGE) method. The current normalized count rate of analytes (Si, Na, Mg, Al and/or B) with respect to prompt gamma-ray at 1273 keV from nuclear reaction $^{29}Si(p,p'\gamma)^{29}Si$ is utilized for the concentration determination[13]. Quality control exercise was carried by analyzing certified/standard reference materials of sodalime and borosilicate glasses. Cross validation of proposed method was carried out by analyzing two different glass samples by three different methods namely in situ current normalized PIGE method using fluorine as current normalizer, external PIGE using tantalum as current normalizer and ED-XRF. Analysis of variance and student's t test were performed to examine the reliability of the results. The optimized method was applied for chemical characterization of forensically important automobile windshield glass samples.

2.1.1. Determination of Isotopic Composition of B in departmental and Industrial B_4C samples

Quantification of total boron and isotopic composition of B (IC, $^{10}B/^{11}B$ atom ratio) in boron-based neutron absorbers is an important step under chemical quality control (CQC) before their applications as control/shut-off rod and neutron shielding materials in nuclear reactors[14-17]. Particle induced gamma-ray emission (PIGE), an ion beam analysis technique, is highly sensitive for quantification of low Z elements and because of its isotope specific nature, isotopic composition can also be determined. This method was found suitable for simultaneous non-destructive determination of isotopic composition of B and total boron mass fraction in direct solid samples with adequate accuracy and precision. It involves irradiation of samples with low energy proton beam (2-5 MeV proton beam of ~10 nA current) and measurement of characteristic prompt gamma rays of 429, 718 and 2125 keV of $^{10}B(p,\alpha\gamma)^{7}Be$, $^{10}B(p,p'\gamma)^{10}B$ and $^{11}B(p,p'\gamma)^{11}B$, respectively. PIGE facility at FOTIA, BARC was utilized and methods have been developed for rapid non-destructive determination of total B and its isotopic composition (IC) simultaneously in diverse ceramic and refractory matrix samples like natural and enriched (with respect to ^{10}B) boron carbide[15], refractory metal borides[17], rare-earth hexaborides, boron composites and alloys relevant to nuclear energy program. For analysis of direct solid powder samples and to increase sample throughput, external PIGE facility was standardized by extracting proton beam in air through a 25 micron Ta foil. Powder samples were wrapped in thin Mylar foil (1 mil thickness), irradiated the target in air under reproducible geometry condition with proton beam (3.5 MeV beam energy on target) and prompt gamma-rays were measured online using HPGe detector set up. The experimental procedure for IC determination using this method along with typical B_4C spectra is shown in **Fig. 10**. Gamma ray peaks from Ta window (136 keV of $^{181}Ta(p,p'\gamma)^{181}Ta$) and nitrogen (2313 keV of $^{14}N(p,p'\gamma)^{14}N$) present in the air were also standardized for their use as an external beam current normalizer for elemental quantification in external PIGE[14-15].

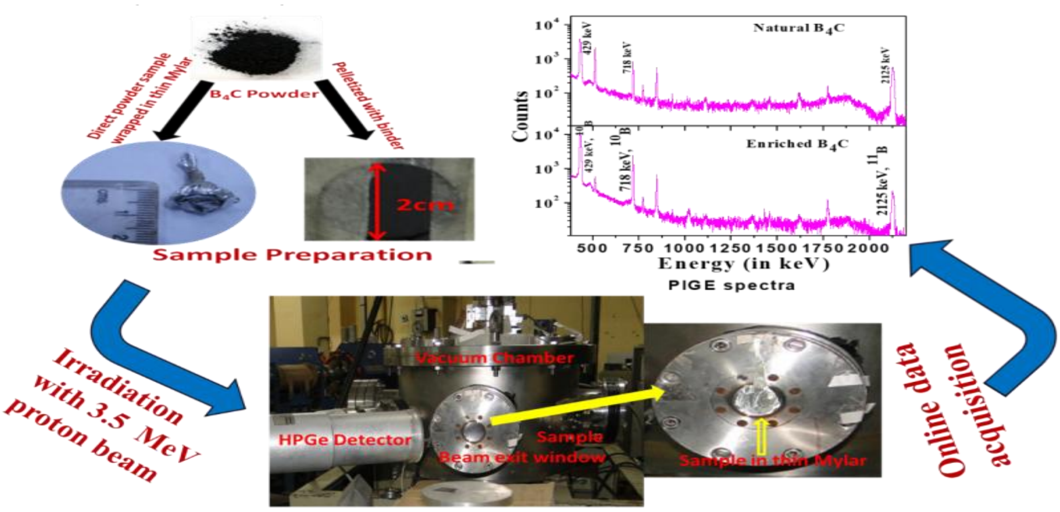


Figure 10. Schematic layout of external PIGE experiment for isotopic composition of Boron

2.1.2.Quality Assessment of Coal and Cement

Quality of coal used for energy production is very important to get high calorific value and lower ash content, though the coal agencies provide different grade coal with their ash content value it is necessary to further check the same before its intended use[18]. Presently, in India, wet chemical analysis is used for quantifying ash content from the oxide concentrations of mainly Si, Al, Fe, Na, Mg, Ca. There is a scope to analyze coal samples by faster nondestructive methods to assess the coal quality with high accuracy and precision. In this respect, neutron and proton based nuclear analytical techniques play a pivotal role for analyzing small to large size coal samples. Ion Beam Analysis (IBA) techniques like PIGE and PIXE using low energy proton beam have been used to determine low Z (Si, Al, Na, Mg) and medium Z (Fe, Ca, Ti) respectively. Total concentration of inorganic constituents (Na, Mg, Al, Si, K, Ca, Ti and Fe oxides) has been used as markers for identifying the quality of coal in terms of coal ash contents. Higher the concentration of inorganic constituents, higher is the coal ash content. Elements such as Sc, Cr, Co, Zn, Se, Cs, Ce, Sm, Hf, U and Th were determined at trace level in coal using conventional NAA techniques. The coal ash content in Indian coal varies in the range from (30 – 40) %. The compressive strength of cement samples depends on Ca to Si ratio. The compressive strengths of C-S-H pastes increases with decreasing Ca to Si ratio. Thus, it is important to determine Ca and Si content in the samples for its quality assessment. Moreover, Ca to Si ratio influences the micromechanical properties of cementitious materials. Ca and Si can be quantified using conventional analytical techniques, but nuclear analytical technique (NAT) is known for being non-destructive, highly sensitive and accurate with very low detection limit. Ca has been estimated in cement samples using NAA with short time irradiation (~1 min). Si has been quantified using external PIGE facility at FOTIA, BARC where the proton beam has been extracted out in air. Ca to Si ratio varies in the range (0.6 – 1.8).

2.1.3. Application to Nuclear waste immobilization

External (in air) PIGE methodology has been optimized for rapid quantification of fluorine, sodium, and phosphorus in fluorapatite waste immobilization matrices for Molten Salt Reactor (MSR)[19]. The present methodology addresses the issue of distinguishing hydroxyapatite and fluorapatite phases through XRD patterns. Fluctuations in proton beam current have been monitored by prompt γ-ray from nitrogen (2312 keV) through $^{14}N(p,p'\gamma)^{14}N$ nuclear reaction and have successfully been applied as a new method of current normalization, for the first time, in external PIGE method with lower

Compton background and negligible spectral interference. The proposed method was also compared with the earlier method of current normalization using 165 keV ($^{181}T(p,p'\gamma)^{181}Ta$) from the Tantalum window used for obtaining "in air" beam. For the fluctuation of beam current within 5–10 nA, nitrogen from air can be used as an effective current normalizer. Moreover, the uncertainty (within ±3%) was also improved in the present method of current normalization. Fluorine can be estimated from trace to major concentrations using 197 keV ($^{19}F(p,p'\gamma)^{19}F$) γ-ray with highest sensitivity as compared to other prompt γ-rays (110 keV and 1236 keV). The matrix effect in PIGE was also eliminated by diluting the sample in cellulose. The method was validated using the synthetic samples ($Ca_{10}(PO_4)_6F_2$, $Na_2Eu_2Ca_6(PO_4)_6F_2$, $Na_{1.5}Eu_{1.5}Ca_7(PO_4)_6F_2$, $Na_1Eu_1Ca_8(PO_4)_6F_2$, $Na_{0.5}Eu_{0.5}Ca_9(PO_4)_6F_2$, and $Sr_{10}(PO_4)_6F_2$). The results were found to be satisfactory and in good agreement with stoichiometric amounts. Elements such as Na, P, and Ca were determined in the fluorapatite samples using PIGE and EDXRF, respectively, as a part of chemical quality control. Moreover, in external PIGE, 1266 keV γ-ray ($^{31}P(p,p'\gamma)^{31}P$) provides more accurate P concentrations in the samples.

3. Conclusions

Nuclear Analytical techniques using neutron and proton as probes from research reactors and particle accelerators are very useful for non-destructive chemical characterization of materials relevant to nuclear technology. Both NAA and IBA have got potential to characterize glass, ceramics, alloys, oxides and carbides (direct solid samples, sometimes "as received samples' too) that are very difficult by conventional spectroscopic techniques. IMNAA with in-situ relative efficiency has been utilized for standardless samples such as alloys and ceramics. PGNAA technique for truly non-destructive nature and bulk analysis property has helped in analyzing finished product with less turnaround time. PGNAA is useful for determination of H and B in various samples. PIGE using low energy proton beam is a potential NATs for low Z elements (Li to S). Besides NAA utilizing research reactors at BARC, conventional and external PIGE facility at FOTIA is used for departmental work program as well as R&D work within BARC, DAE and with Universities/ Academic / Research Institutes for collaborative projects / work program with support from UGC-DAE-CSR Scheme with or without Projects. External PIGE Facility with thin Tantalum as beam exit window is a unique and first of a kind (FOAK) facility in BARC as well as in India for rapid analysis of "as received" samples of small and larger sizes for determination of low Z elements in glass, ceramics. refractory materials, shielding materials, control rod and even liquid / water samples. For the first time, in August 2023, External PIGE facility at FOTIA was utilized for commercial application to certify ^{10}B isotope content in natural B_4C samples obtained from M/s Bhukhanvala Industries Pvt. Ltd., Mumbai.

Acknowledgements

The article containing R&D work has been carried out by the Author during 1994-2024 at RCD, RC&IG, BARC. Author is thankful to all contributors and collaborators from BARC, DAE and other Institutes for their contributions. Author thanks senior colleagues/mentors Dr SB Manohar, Dr AVR Reddy, Dr AGC Nair, Dr A Goswami and Dr P K Pujari and younger colleagues from BARC namely Dr Kathi Sudarshan, Dr K. K. Swain, Mr Sk Wasim Raja, Mr S K Samanta, Mrs.Sonika Gupta, Mrs. Priya V Mestry and from BARC (HBNI)-University collaborative PhD scheme namely Dr Kishore Babu Dasari (UGC DAE CSR PhD, presently Research Scientist at KAERI-KRISS), Dr Sumit Chillar (HBNI) and Mr Vishal Sharma (then CSIR-SRF working at RCD currently Scientist (NAA) at CFSL, Hyderabad) for their R&D contributions which have been reflected in this article. Author also thanks all co-authors/collaborators from BARC & other institutes for other contributions towards food, agriculture & environment, which are not part of this article Author is thankful to Dr. Y.K. Bhardwaj, Associate Director, RC&IG and Director, RC&IG, BARC for their support and encouragement. Author sincerely thanks Operating personnel of research reactors (Dhruva and Apsara-U) and particle accelerators of BARC (FOTIA & TIFR) and all concerned authorities of respective Divisions and Groups for their direct or indirect help and support.

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Brief Biodata

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Chapter 7: Radiopharmaceuticals Applications and Recent Advancements in Radiopharmaceuticals

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Abstract: *Radioisotopes have revolutionized the field of healthcare, offering powerful tools for diagnosis and treatment of various diseases. These unstable atoms play a vital role in modern healthcare, aiding in the diagnosis of various diseases such as Alzheimer and Parkinson disease, thyroid disorders, cardiovascular disease, renal failure, liver dysfunction, and even cancer. In addition to diagnosis, radioisotopes also play a vital role in cancer treatment. 'Nuclear medicine' employs the nuclear decay properties of radioisotopes for diagnostic evaluation of disease conditions or for therapeutic purposes to cure diseases. Nuclear medicine procedures involve the administration of a small amount of radiochemical preparation called "Radiopharmaceutical" to a patient for the diagnosis or treatment of diseased condition.*

1. Radiopharmaceuticals

Radiopharmaceuticals are radiochemical formulations or radiolabeled drugs with a constant composition and can be administered either orally or intravenously with adequate safety, for the purpose of carrying out diagnosis or treatment of a diseased condition, particularly of cancerous origin [1]. The radiopharmaceutical has two components: a 'radionuclide' and an organic, inorganic, medicinal or a natural compound, 'pharmaceutical' in a definite composition. The usefulness of radiopharmaceutical for a particular application is governed by the characteristics of these two components. The nature and structural activity of the radiopharmaceutical molecule dictates its specificity towards particular organ/tissue while the nuclear decay properties of the tagged radionuclide contribute towards the diagnostic or therapeutic efficacy of the radiopharmaceutical [2,3].

1.1. Classification of Radiopharmaceuticals

1.1.1. Metal essential and metal non-essential radiopharmaceuticals

Radiopharmaceuticals can be either metal-essential or metal non-essential based on the type of organic molecule. In metal essential radiopharmaceuticals, the carrier molecule do not have any biological activity or specificity towards a particular target on their own, the biological distribution is decided by the whole metal-complex based on its physical and chemical properties. Structures of some of the metal essential radiopharmaceuticals are shown in **Figure 1.**

In the latter case, metal is not essential for the biological properties of the radiopharmaceutical and the ultimate biodistribution of the agent is determined by the carrier molecule. Metal non-essential radiopharmaceuticals are often called as target-specific radiopharmaceuticals.

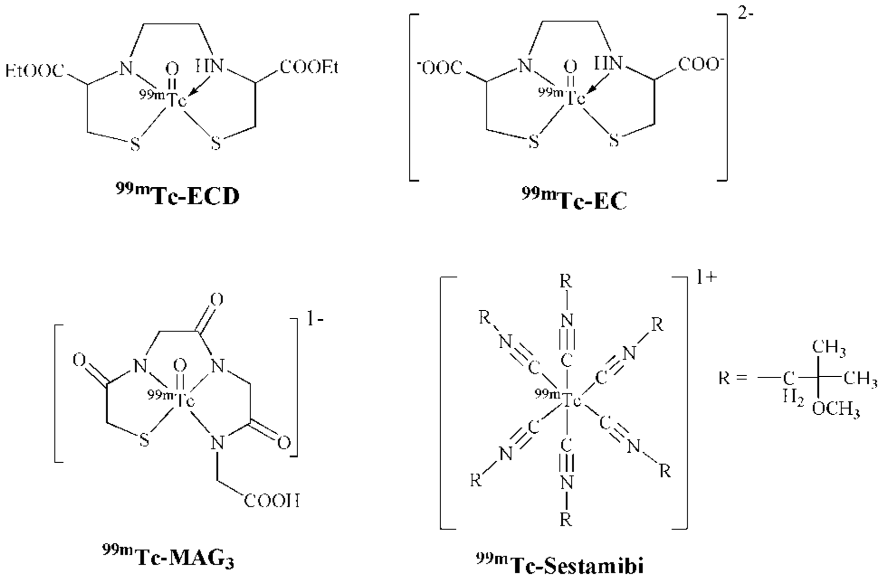
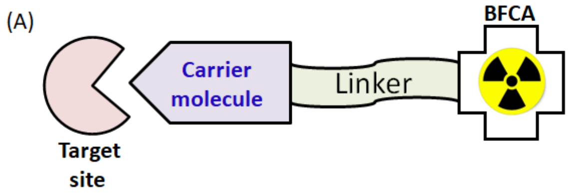


Figure 1: Structures of few metal essential radiopharmaceuticals

The high specificity of the carrier molecule towards specific receptor results in selective uptake of the radiopharmaceutical at the diseased site and thus has the ability to accurately target the tumor lesions/cancer while sparing the non-target organs/tissue [3,4]. Target specific radiopharmaceuticals are prepared in two ways: direct radiolabeling approach or using a bifunctional chelating agent (BFCA). Direct radiolabeling approach is mostly used for incorporation of non-metallic radionuclides like ^{131}I, ^{125}I, ^{123}I, ^{18}F etc. into the desired biologically active target molecule. However, for the incorporation of radiometals into these target-specific biomolecules the most reliable and most frequently applied method is by means of a BFCA [3,4]. Schematic representation of design of a target specific radiopharmaceutical is shown in **Figure 2 (A)**. BFCA is a small molecule containing two different moieties. One being a chelating unit which strongly coordinates with the metal ion and other moiety is a functional group able to react and form stable covalent bond with the targeting molecule. The BFCA serves as a bridge between the biomolecule and the radionuclide and normally do not have any specific biological reactivity. Examples of few target-specific radiopharmaceuticals are ^{177}Lu-DOTA-TATE, ^{99m}Tc-HYNIC-TATE, ^{68}Ga-DOTA-TATE, ^{68}Ga-PSMA etc. Structure of ^{177}Lu-DOTA-TATE is shown in **Figure 2 (B)**, where DOTA is the BFCA which tightly binds the radionuclide (^{177}Lu) and forms stable bond with the targeting peptide (octreotide).

1.1.2. Diagnostic Radiopharmaceuticals

Diagnostic radiopharmaceuticals are radiolabeled molecules, which are designed to produce images of the morphology or physiological functions of specific organs/tissue. In diagnostic radiopharmaceutical radioisotope used is either a gamma emitter or a positron emitter. Gamma radiations have low LET and hence can penetrate through the patient's body and can be detected by external detectors. In case of positron emitting radioisotopes, positively charged positron interacts with the negatively charged electron present in the surrounding medium and an annihilation reaction occurs. The annihilation reaction results in two 511 keV gamma rays emitted in opposite directions which are detected simultaneously to construct the image. Single photon emission tomography (SPECT) and positron emission tomography (PET) are the two imaging modalities used in nuclear medicine depending on the type of emission by the radionuclide. List of commonly used radionuclides for SPECT and PET imaging is presented in **Table-1 (A) and (B).**



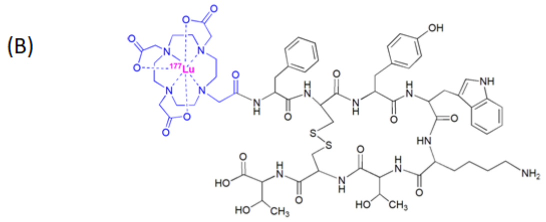


Figure 2: (A) Typical design of a target-specific radiopharmaceutical using BFCA approach and (B) Structure of ^{177}Lu-DOTA-TATE

Table-1 (A): List of commonly used radionuclides for SPECT imaging

Radionuclides	**Half-life ($T_{1/2}$)**	**Mode of decay**	**Eγ in keV (% Abundance)**
^{99m}Tc	6.02 h	IT	140.5 (89.0)
^{123}I	13.27 h	EC	159.0 (82.8)
^{67}Ga	3.26 d	EC	93.3 (38.3)
^{111}In	2.80 d	EC	245.4 (94.2)
^{201}Tl	72.91 h	EC	167.4 (10.0)

Radiopharmaceuticals labeled with PET and SPECT radionuclides have proven highly effective in diagnosing conditions such as tumors, neurological and neurodegenerative disorders, inflammation, and bacterial infections [5,6]. As a result, nuclear medicine imaging using PET and SPECT plays a crucial role in various healthcare areas, providing routine, non-invasive methods for diagnosing and predicting the progression of many diseases.

Among different radioisotopes used in diagnostic nuclear medicine, ^{99m}Tc with its ideal nuclear characteristics ($t_{1/2}$ = 6 h, E_γ = 140 keV), cost effectiveness, easy availability from ^{99}Mo/^{99m}Tc generator and ready formulation of radiopharmaceuticals through cold kits, occupies a premier position in nuclear medicine. ^{99m}Tc continues to be the 'work-horse' of diagnostic Nuclear Medicine and is routinely and most widely used medical isotope accounting for approximately 30 million diagnostic procedures annually comprising ~80% of all diagnostic Nuclear Medicine procedures worldwide [7-9].

Table-1 (B): List of commonly used radionuclides for PET imaging

Radionuclide	**Half-life ($T_{1/2}$)**	**Mode of decay**	**E_{max} in MeV (% Abundance)**
^{18}F	109.8 min	β^+	0.63 (96.9)
^{11}C	20.4 min	β^+	0.96 (99.8)

^{13}N	10.0 min	β^+	1.20 (99.8)
^{15}O	2 min	β^+	1.73 (99.9)
^{68}Ga	68 min	β^+/EC	1.90 (89.1)
^{64}Cu	12.7 h	β^+/EC	0.65 (17.5)
^{124}I	4.18 d	β^+/EC	2.14 (12)
^{89}Zr	78.4 h	β^+/EC	0.90 (22.8)

While SPECT remains a key diagnostic tool in nuclear medicine, PET is rapidly becoming the standard for many clinical indications due to its higher sensitivity, better resolution, and ability to provide more detailed functional imaging [10,11]. The continued development and availability of PET radiopharmaceuticals will further drive this transition, offering new opportunities for early disease detection and more precise treatment monitoring. ^{18}FDG is the most widely used PET radiopharmaceutical in clinical oncology. The availability of ^{68}Ga from ^{68}Ge/^{68}Ga generator has ensured feasibility of cyclotron-independent production of PET radiopharmaceuticals at nuclear medicine departments. Further, the application of PET in clinical oncology is increasing since many molecular targets relevant to cancer can be easily radiolabeled with ^{68}Ga due to the simple co-ordination chemistry of Ga^{3+}. ^{68}Ga-labelled peptides targeting receptor over expression at cancer sites have been extensively studied and are at different stages of development. ^{68}Ga labeled somatostatin analogs (^{68}Ga-DOTA-TATE/TOC/NOC) are routinely used for diagnosis, staging and monitoring the therapeutic response in patients suffering from neucroendocrine tumors (NETs) [12,13]. ^{68}Ga-PSMA-11 is an FDA approved radiopharmaceutical for the diagnosis of prostate specific membrane antigen (PSMA) specific prostate cancer [14].

More recently, ^{64}Cu-labeled molecules have emerged as promising imaging agents for PET due to the favorable nuclear characteristics of the isotope ($t_{1/2}$ = 12.7 h, β^+ 17.4%, E_{max} = 0.656 MeV, β^- 39%, E_{max} = 0.573 MeV) and its availability in high specific activity. The longer physical half-life of ^{64}Cu compared to ^{18}F ($t_{1/2}$ = 110 min) and ^{68}Ga ($t_{1/2}$ = 68 min) enables imaging at delayed time points, which allows sufficient time for clearance from background tissues, resulting in increased image contrast, particularly for targeting agents that demonstrate long circulation times such as antibodies and nanoparticles [15].

The primary advantage of diagnostic radiopharmaceuticals is their ability to provide detailed images of both anatomical and functional aspects of the body, often at much earlier stages than conventional imaging techniques such as X-rays or MRIs. This capability enables earlier diagnosis, which can be critical in the effective treatment of many diseases. Some of the diagnostic radiopharmaceuticals used in nuclear medicine are given in **Table 2**.

1.1.3. Therapeutic radiopharmaceuticals

The use of a radiopharmaceutical for therapeutic application is based on the strategy that the radiations emitted deposit maximum amount of energy in the shortest time to the proliferating cancer cells while sparing the surrounding normal cells from unwanted radiation.

Table 2: List of diagnostic radiopharmaceuticals used in nuclear medicine

Radiopharmaceutical	Application
^{99m}Tc-ECD, ^{99m}Tc-TRODAT, ^{99m}Tc-HMPAO	Brain imaging
^{99m}Tc-Sestamibi, ^{99m}Tc-Tetrofosmin, ^{201}TlCl	Cardiac imaging

^{99m}Tc-Sulphur colloid	Liver imaging
^{99m}Tc-Mebrofenin	Hepatobiliary function
^{99m}Tc-MAA, ^{68}Ga-MAA	Lung imaging
^{99m}Tc-MDP, ^{68}Ga-BPAMD, Na^{18}F	Bone imaging
^{99m}Tc-GHA, ^{99m}Tc(III)-DMSA, ^{99m}Tc-DTPA, ^{99m}Tc-EC, ^{99m}Tc-MAG$_3$	Kidney imaging
^{99m}Tc-Leuocytes, ^{99m}Tc-ciprofloxacin, ^{99m}Tc-UBI	Infection/Inflammation imaging
^{18}F-FDG	Cancer diagnosis
^{99m}Tc-HYNIC-TOC/TATE, ^{68}Ga-DOTA-TOC/TATE	Diagnosis of NETs
^{68}Ga-PSMA	Diagnosis of prostate cancer

In therapeutic radiopharmaceuticals, particulate emitting radioisotope is tagged to the monoclonal antibodies, nanoparticles, peptides, and small molecules for targeted delivery of cytotoxic dose of ionizing radiation. List of particulate emitting radionuclides used for therapeutic application are presented in **Table 3.** Unlike radiotherapy, the radiation is not administered from outside the body, but instead is delivered systemically or loco-regionally. Thus, radiopharmaceutical therapy ensures that a concentrated dose is delivered to the targeted tissue while preserving the surrounding normal tissues. Several radiopharmaceuticals are currently being used for therapeutic applications for both curative and palliative treatment by absorption and subsequent destruction of diseased cells. Therapeutic radiopharmaceuticals have shown promising potential in several major areas, particularly in the treatment of cancer and certain non-cancerous conditions. Some of the key areas are:

Table 3: List of therapeutic radionuclides

Radionuclide	**Half-life ($T_{1/2}$)**	**Mode of decay**
^{177}Lu	6.71 d	& γ
^{166}Ho	26.80	β^- & γ
^{153}Sm	46.28 h	β^- & γ
^{131}I	8.02 d	β^- & γ
^{186}Re	90.64 h	β^- & γ
^{188}Re	16.98 h	β^- & γ
^{89}Sr	50.57 d	β^-
^{90}Y	64.10 h	β^-
^{32}P	14.26 d	β^-
^{225}Ac	10.00 d	α & γ
^{223}Ra	11.44 d	α & γ

1.1.3.1. Radioactive iodine therapy in thyroid diseases

The treatment of benign and malignant diseases of the thyroid can be done with I-131. Radioiodine therapy has been used for a long time. In treating diseases such as hyperthyroidism, I-131 radionuclide settles in the thyroid tissue. It destroys the follicle cells with the beta particles it emits and stops the growth and activities of the thyroid cells. In this case, it returns the functions of the overactive thyroid gland to normal. In malignant diseases such as thyroid cancer, radioactive iodine therapy can also be applied to remove residual thyroid gland residues after thyroid surgery and treatment of the spread of thyroid cancers in the body [16,17].

1.1.3.2. Metastatic bone pain palliation

Bone-seeking radiopharmaceuticals emitting β^--particles have long been used for bone-pain palliation. ^{32}P in the form of $Na_3{}^{32}PO_4$, ^{89}Sr in the form of $^{89}SrCl_2$ (Metastron®), ^{153}Sm as ^{153}Sm-EDTMP (Quadramet®), ^{177}Lu as ^{177}Lu-EDTMP and ^{188}Re as ^{188}Re-HEDP (HEDP = hydroxyethylenediphosphonate) are approved agents for pain palliation in patients suffering from skeletal metastases [18]. Recently α-emitting tracer, $^{223}RaCl_2$ (trade name Xofigo) was developed for bone pain palliation. Radium is preferentially absorbed by bone by virtue of its chemical similarity to calcium. Alpha radiation has very short range in tissues, around 2-10 cells, compared to beta or gamma radiation. This reduces damage to surrounding healthy tissues, producing an even more localized effect than the β^--emitter strontium-89.

1.1.3.3. Liver cancer therapy

Therapeutic radiopharmaceuticals are becoming increasingly important in the treatment of liver cancer, particularly hepatocellular carcinoma (HCC), the most common type of primary liver cancer. Yttrium-90 (^{90}Y) intra-arterial radiotherapy using ^{90}Y containing solid glass microspheres (microscopic glass beads of 20-30 μm in diameter) (TheraSphere®) also known as radioembolization, is a technique for the treatment of patients with unresectable primary or metastatic liver tumors [19]. Y-90 microspheres are delivered directly to the tumor through the hepatic artery. Since liver cancer cells are highly vascularized through this artery, the microspheres preferentially accumulate in the tumor, delivering localized radiation to destroy cancerous cells while minimizing damage to healthy tissue. Bis-(diethyldithiocarbamato)nitrido rhenium-188 (^{188}ReN-DEDC) is another approved agent for the treatment of HCC [20]. Therapeutic radiopharmaceuticals are a promising tool in the treatment of liver cancer, particularly for inoperable or advanced stages of disease.

1.1.3.4. Peptide receptor radionuclide therapy

Peptide receptor radionuclide therapy (PRRT) is a site-directed targeted therapeutic strategy that specifically uses radiolabeled peptides as biological targeting vectors designed to deliver cytotoxic levels of radiation dose to cancer cells, which overexpress specific receptors. Interest in PRRT has steadily grown because of the advantages of targeting cellular receptors in vivo with high sensitivity as well as specificity and treatment at the molecular level. Nearly all cancers have overexpression of specific receptors on the tumor surface, which forms the basis of peptide receptor radionuclide therapy (PRRT). The most widely employed modality of PRRT uses radiolabeled somatostatin analogues for targeting somatostatin receptors (SSTR), which are over-expressed in NETs. ^{177}Lu-DOTA-TATE is an FDA approved agent for the treatment of SSTR expressing NETs [21,22]. Radiolabeled peptides targeting PSMA receptor have emerged as promising agents for diagnosis and therapy of PSMA expressing prostate cancer. ^{177}Lu-PSMA-617 is currently in phase III randomized trials for the treatment of metastatic castration-resistant prostate cancer [23]. In recent years, targeted alpha therapy (TAT) using ^{225}Ac-DOTA-TATE and ^{225}Ac-PSMA has emerged as a promising treatment modality in the management of neuroendocrine cancers and prostate cancers respectively [24-26].

1.1.3.5. Radioimmunotherapy

Radioimmunotherapy (RIT) uses an antibody labeled with a radionuclide to deliver cytotoxic radiation to a target cell. In cancer therapy, an antibody with specificity for a tumor-associated antigen is used to deliver a lethal dose of radiation to the tumor cells. The ability for the antibody to specifically bind to a tumor-associated antigen is the basic principle of this therapy. Zevalin (^{90}Y-Ibritumomab Tiuxetan) is the first radiolabeled antibody approved by US-FDA and is used for the treatment of Non-Hodgkins' Lymphoma (NHL). Bexxar (^{131}I-labeled-Tositumomab) is another radiolabeled antibody approved for RIT of NHL. However, both of these antibodies are of murine origin and give rise to HAMA (human anti mouse antibody) response inside the body which is undesirable. To circumvent this, genetically engineered antibodies having human component were synthesized, radiolabeled and currently are in clinical trials. For example: ^{177}Lu-trastuzumab and ^{177}Lu-rituximab are currently in different stages of clinical trials worldwide for evaluation of their efficacy for the radioimmunotherapy of HER2 positive breast cancer and CD20 positive non-Hodgkin's lymphoma respectively [27].

1.1.4. Theranostic Radiopharmeuticals

Theranostic radiopharmaceuticals are a class of radiopharmaceuticals that combine both therapeutic and diagnostic properties in a single agent. The term theranostic is a blend of "therapeutic" and "diagnostic," and it refers to the use of the same or similar radiopharmaceutical for both diagnosis and treatment of diseases, particularly cancer. Theranostic radiopharmaceuticals enable personalized medicine approaches, allowing clinicians to tailor treatment strategies based on individual patient characteristics. There are three different possibilities by which theranostics can be employed in radiophrmaceuticals. (i) Theranostic pairs combining two radiopharmaceuticals that share the same structure and target but are differentially labelled with matching radioisotope pairs that allow diagnosis and therapy separately. Some of the examples are ^{99m}Tc (for diagnostic purpose) and ^{188}Re (for therapeutic purpose), ^{68}Ga (for diagnostic purpose) and ^{177}Lu (for therapeutic purpose) etc. (ii) Radiopharmaceuticals prepared by using radioisotopes of the same element, such as ^{123}I (for diagnostic purposes) and ^{131}I (for therapeutic purposes). (iii) Radiopharmaceuticals prepared using a radionuclide which decays by particulate emission along with imageable γ photons (e.g. ^{177}Lu, ^{166}Ho) [28].

2. Conclusion

Radiopharmaceuticals have made significant progress in recent years, improving both cancer treatment and diagnosis. New developments in targeting agents, better radionuclide choices, and advanced delivery systems are driving the growth of this field. The development of theranostic radiopharmaceuticals has paved the way for personalized medicine, providing patients with more targeted and effective treatment options.

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Dr. Tapas Das is presently working as Head, Radiopharmaceuticals Division of Bhabha Atomic Research Centre (BARC), Mumbai. He had joined DAE in 1998 after completing his post-graduation in Chemistry and one-year OCES Program from 41st batch of BARC Training School. He had obtained Ph.D. from University of Mumbai in 2004. His research field of interest includes production of radioisotopes and development of radiopharmaceuticals for diagnostic and therapeutic applications. He has received several awards such as, Prof. H.J. Arnikar Best Thesis Award, Tarun Datta Memorial Young Scientist Award, DAE Young Scientist Award, DAE Scientific & Technical Excellence Award and multiple DAE Group Achievement Awards. He has served as Technical Co-operation Expert and Consultant of International Atomic Energy Agency (IAEA, Vienna, Austria). He is a 'Professor' of Chemical Sciences and recognized Ph.D. Guide of Homi Bhabha National Institute (HBNI), Mumbai. Dr. Das is a fellow of Maharashtra Academy of Sciences and one of the Editors of the journal 'Applied Radiation and Isotopes' (published by Elsevier). He is also the Editorial Board Member of BioMed Research International (published by Wiley) and Indian Journal of Nuclear Medicine. Dr. Das has published 112 research articles in various peer-reviewed international journals.

Chapter 8: Boron Neutron Capture therapy: current status and historical perspective

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Abstract: *Boron Neutron Capture Therapy (BNCT) is an advanced radiation treatment known for its precision in targeting tumors. It involves a nuclear reaction where Boron-10 (10B) is exposed to thermal neutrons, producing alpha particles (Helium-4) and recoiling lithium-7 nuclei. For effective treatment, a high concentration of Boron-10 must be present in cancer cells, and a sufficient number of thermal neutrons must be absorbed to induce a lethal (n, α) reaction. BNCT has shown clinical success in treating aggressive tumors like gliomas, melanomas and osteosarcomas. The development of innovative boron-containing compounds has fueled research into improving BNCT outcomes. This review focuses on advancements in boron carriers over the past decade, discussing challenges and providing recommendations for enhancing boron delivery systems for clinical application.*

1. Introduction

Cancer is a leading cause of death worldwide, encompassing a wide range of diseases caused by abnormal cells that grow uncontrollably. These cells can spread beyond their usual boundaries, invade surrounding tissues, and even spread to other organs. The increasing incidence of cancer, with a projected rise of 47% by 2025 compared to 2020, highlights the urgent need to improve cancer prevention, screening, diagnosis, and treatment strategies. Cancer imposes a significant economic burden and remains a major global health challenge [**1,2**].

Traditionally, chemotherapy and radiotherapy have been the main treatments for cancer. However, these therapies have limitations, particularly regarding their therapeutic effectiveness and the adverse effects they can have on normal tissues. Therefore, new approaches are necessary to overcome these challenges [**2, 3**]. Biological therapies, such as immunotherapy (including immune checkpoint inhibitors and engineered cellular therapies like chimeric antigen receptor (CAR)-modified T cells), have attracted significant attention due to their higher therapeutic efficacy and reduced toxicity [**2].** In radiation therapy, advanced techniques like boron neutron capture therapy (BNCT), proton beam therapy, and carbon-ion radiotherapy offer improved biological and physical dose distributions with higher relative biological effectiveness compared to conventional photon therapy **[4,5].**

BNCT, in particular, is a tumor-selective radiotherapy that combines the benefits of biological targeting with heavy ion radiation **[6]**. It is a non-invasive, organ-preserving treatment that can be applied in one or more sessions, making it effective for treating diffuse or irregularly shaped tumors [**5].** BNCT is considered a binary treatment, involving the administration of a boron-containing drug (10B, a non-radioactive isotope) that preferentially accumulates in tumor cells, followed by irradiation with thermal or epithermal neutron beams [**7,8].** BNCT has become a promising and advanced modality of radiation therapy that has evolved significantly with the development of neutron sources from accelerators, which can produce epithermal neutron beams. This progress has been further accelerated by the collaborative efforts of interdisciplinary teams and international partnerships, which have contributed to the expansion of this treatment technique [**9, 10].**

2. Mechanism of action

The core principle behind all radiation therapies is to deliver a tumor-destroying dose of radiation to the tumor while minimizing the exposure of healthy tissues. Radiation therapy is generally administered through three clinical modalities: external beam radiation therapy (EBRT), brachytherapy, and systemic radionuclide therapy **[11-14]**. Each method has its own mechanism, benefits, and limitations. EBRT is the most widely used treatment for cancer and employs different types of ionizing radiation (such as electron, photon, proton) with varying radiobiological effectiveness (RBE). Both EBRT and brachytherapy target the tumor at the macroscopic level using imaging techniques like computed tomography (CT) or magnetic resonance imaging (MRI). Systemic radionuclide therapy, on the other hand, delivers radioactive isotopes via the bloodstream to specifically target cancer cells.

Boron neutron capture therapy (BNCT) stands apart by delivering charged particles directly to the tumor at the cellular level **[15]**. In BNCT two separate non-toxic components are used, which on their own are harmless but become highly destructive to cancer cells when used together. Neutrons, which have no charge, pass through normal tissues without significant interaction, as their primary mode of action is the nuclear capture by stable nuclei such as 1H, 14N and 10B. Living tissues contain plenty of 1H (0.33 barns) and 14N (1.7 barns), but because of their low capture cross-section, reactions with these elements occur infrequently and do not result in harmful radiation damage to healthy tissues. In contrast, 10B (with a much higher capture cross-section of 3990 barns) is rare in living tissues but highly reactive with neutrons. This higher concentration of boron while bombarded with neutron beam directed at tumor lesion causes a reaction, resulting in damage to the cancer cells **(Figure 1).**

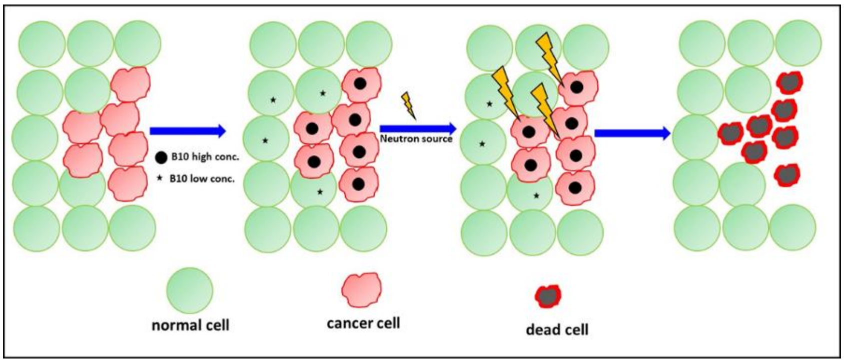

Figure 1. Cellular schematic of boron neutron capture therapy

BNCT relies on nuclear capture and fission reactions that occur when non-radioactive 10B is irradiated with slow (thermal) neutrons of the appropriate energy. This interaction produces excited 11B, which undergoes an immediate nuclear reaction to release a high-energy α particle and a high-energy 7Li nucleus. The nuclear reaction is as follows:

$$\boxed{{}^{10}\mathrm{B} + \text{Thermal neutron} \longrightarrow [{}^{11}\mathrm{B}]^{*} \longrightarrow \alpha + {}^{7}\mathrm{Li} + 2.31\ \mathrm{MeV}}$$

Alpha particles and lithium nuclei are charged particles with high linear energy transfer (LET) and relative biological effectiveness (RBE), causing closely spaced ionizations near the site of the reaction. These particles have ranges of approximately 5 µm (α particles) and 9 µm (lithium nuclei) and deposit dose at 175 keV/µm and 150 keV/µm, respectively. For context, the diameter of an oral cavity squamous cell is about 80 µm. The tumoricidal radiation from these particles is confined to the boron-containing cells, which limits the damage to normal tissues. Thus, successful BNCT depends on two key factors: (1) the selective delivery of a sufficient amount of 10B to the tumor, with minimal normal tissue concentration, (2) the presence of thermal neutrons with proper energy and flux to trigger the reactions.

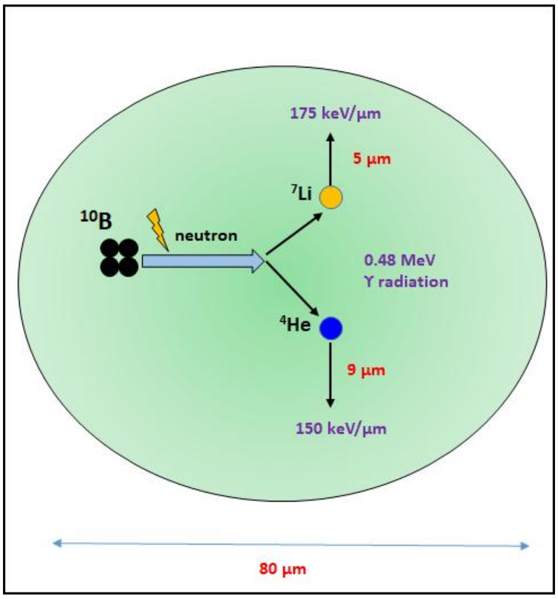

Figure 2. Intracellular mechanism of boron neutron capture therapy.

3. Historical milestone in BNCT

Groundbreaking technologies are rarely the result of a single individual's work. Instead, their success is often built upon the contributions of many others over time. Boron neutron capture therapy (BNCT) is no exception. The concept of neutron capture therapy was first proposed in the mid-1930s by astrophysicist Gordon Locher, who suggested that neutrons emitted from a radium source, when captured by beryllium, could be used to selectively kill tumor cells **[16].** This marked the first mention of "fast neutron capture." Later, in 1935, nuclear physicist Moritz Goldhaber found that the "slow neutron boron reaction" produced short, linear microscopic tracks in photographs filled with borax **[17**]. However, progress in this field stalled briefly due to the global focus on World War II, which shifted attention and resources away from many scientific projects. While the war accelerated critical advancements in nuclear physics, BNCT was not immediately prioritized. Nevertheless, the war's conclusion highlighted the power of the atom, prompting a global race to explore its potential. Nuclear reactors initially developed for destructive purposes were eventually repurposed for other uses, including some for clinical medicine.

Neurosurgeon William Herbert Sweet and physicist Gordon Lee Brownell, affiliated with Massachusetts General Hospital and the Massachusetts Institute of Technology (MIT), respectively, initiated the first clinical trials of Boron Neutron Capture Therapy (BNCT) in 1951, utilizing the Brookhaven Graphite Research Reactor [**18-20].** Following the primary debulking craniotomy performed on patients diagnosed with high-grade glioma in Cambridge, Massachusetts, Sweet transported these individuals to Upton, New York, for the intravenous administration of 10B-enriched borax (sodium tetraborate). Subsequently, he exposed the patients to a single dose of thermal neutrons from the experimental reactor. Unfortunately, none of the patients in these initial trials survived beyond one year, and all experienced significant toxic effects. A retrospective analysis indicated that inadequate tumor-to-blood ratios (TBRs) due to surgical debulking hindered the effective compartmentalization of boron, which likely contributed to the unfavorable outcomes observed in Sweet's early patient cohort with glioma [**21].** It is crucial to recognize that thermal neutrons have limited penetration depth; thus, open craniotomies with exposed surgical sites were necessary to ensure sufficient dose delivery. Sweet's pioneering efforts and the recognition of their shortcomings prompted collaborations aimed at enhancing the selectivity and delivery of boronated compounds. Chemist Albert Herman Soloway joined the team, discovering new boronated compounds with improved pharmacokinetic properties. Concurrently, pediatrician Lee Edward Farr contributed his expertise in researching boronated compounds for clinical BNCT applications at Brookhaven National Laboratory [**19**]. The trials progressed, and in 1960, Sweet administered intravenous paracarboxyphenylboronic acid to 16 glioblastoma patients, utilizing the MIT Research Reactor, but again faced similarly disappointing outcomes. Following this, he administered intra-arterial sodium decahydrodecaborate via the internal carotid artery to two patients. Autopsy results indicated that these patients succumbed to cerebral edema, which was believed to have resulted from the treatment. In 1961, the advancement of BNCT was impeded by toxicities and disappointing outcomes, along with an increasing domestic apprehension surrounding all nuclear-related projects.

In 1968, Hiroshi Hatanaka, a mentee of Sweet, initiated a clinical program in Japan. Years later, Hatanaka presented some of the most remarkable clinical outcomes ever documented for high-grade gliomas **[22**]. Although the majority of the patients treated had astrocytomas, with a few glioblastomas included, the reported median survival was 21.3 months. In contrast, even with the current standard treatment for glioblastomas, which involves craniotomy followed by the Stupp protocol of radiation and temozolomide, the median survival is only 14.6 months **[23]**. These impressive results may have been influenced by the improved pharmacokinetics of sodium borocaptate (BSH, $Na_2B_{12}H_{11}SH$). The EORTC 11961 study, which examined the biodistribution of BSH in glioblastoma patients, indicated that the tumor-to-normal brain ratio could be as high as 40 to 1 **[24, 25]**.Shortly thereafter, Japanese dermatologist Yutaka Mishima introduced a second drug, experimenting with perilesional injections of 4-borono-d,l-phenylalanine (BPA) in malignant melanomas, marking one of the earliest extracranial applications **[26,27]**. As additional tumor histological patterns were found to effectively absorb BPA, it became the most commonly utilized boronated compound. Subsequently, fructose was conjugated to enhance its hydrophilicity. In the early 1990s, a transition occurred from using the racemic form to the L-enantiomer. The l-BPA, synthesized by John David Glass, emerged as the leading boronated compound for clinical trials **[28]**. Wittig et al. discovered that BPA is actively transported into cells via the l-amino acid transport system, which is tightly regulated in most tumors, allowing BPA to target a diverse range of tumor types **[29]**.

Consequently, a 30-year pause in the use of BNCT concluded in the 1990s with the revival of clinical programs at Brookhaven, MIT, Finland, the European Union, and Japan. The modern era of BNCT was characterized by the application of second-generation compounds, l-BPA and BSH, although neutrons were still utilized from reactors itself.

Available data on prospective BNCT is limited, with merely 17 clinical trials recorded by the National Institutes of Health. The diseases examined in these trials were restricted to head and neck cancers, melanomas, and glioblastomas. Out of the 17 trials, 4 were discontinued, 4 ceased updates, and 2 did not publish their findings, resulting in 7 completed studies **[30-35]**. The in general procedure for BNC therapy is given in the following schematic (Figure 3).

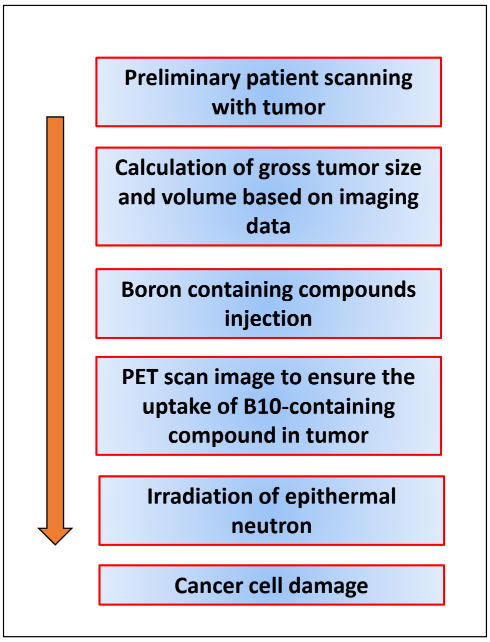

Figure 3. Block diagram of procedure for boron neutron capture therapy.

4. Properties of Boron based compounds and their classification

There are certain prerequisite for boron compounds to be used in BNCT. They should exhibit low systemic toxicity, with normal tissue absorption coupled with elevated uptake in tumors. The main goal is to achieve tumor to normal tissue ration more than 4:1 **[36].** There are currently three generations of boron compounds, each being continually refined to improve their ability to selectively target tumor cells while maintaining relatively low toxicity to the organism.

4.1. 1st generation

During the 1950s and early 1960s, boric acid and its derivatives were employed as delivery agents in clinical trials. These compounds were simple chemicals, lacked selectivity, had limited tumor retention, and showed low tumor-to-brain ratios.

4.2. 2nd generation

BPA and BSH are two additional boron compounds that were introduced in the 1960s. They demonstrated significantly reduced toxicity and persisted in animal tumors for extended periods when compared to analogous molecules. Furthermore, they exhibited tumor-to-brain and tumor-to-blood boron ratios exceeding 1. These compounds continue to be extensively utilized in various research studies and clinical trials today.

4.3. 3rd generation

These compounds consist of stable boron clusters connected by a hydrolytically stable linker to a tumor-targeting component, known as Boron Carriers. A variety of biomolecules, both low and high molecular weight, such as mitochondria, lysosomes, endoplasmic reticulum, Golgi apparatus, nucleosides, sugars (e.g., BPA-fructose), porphyrins, liposomes, and monoclonal antibodies (mAb), have been used as tumor-targeting agents **[37]**. These third-generation boron compounds are specifically designed to target tumor cells, especially the nucleus and DNA, which are ideal sites for these agents. Moreover, the amount of boron required to produce a lethal effect can be significantly reduced if concentrated within or near the nucleus. Ongoing research continues to investigate these agents. Notably, the BPA-fructose complex was used in 1994 for the treatment of glioblastoma in patients undergoing Boron Neutron Capture Therapy (BNCT) **[38].**

5. Neutron Source for BNCT

Neutrons intended for Boron Neutron Capture Therapy (BNCT) must be supplied at a high flow rate and possess the appropriate energy levels. The radiation beam aimed at the tumor site should contain minimal impurities. Neutrons suitable for epithermal radiation are produced by Nuclear Reactors and Accelerator-Based Neutron Sources (ABNS). The biggest obstacle to the adoption of BNCT has been the need for direct access to a nearby nuclear reactor, which continues to create a significant barrier to equitable care. While BNCT holds promise as the ultimate precision medicine solution, the financial challenges of launching a new clinical program are overshadowed by the logistical requirement of having a nuclear reactor.

The future potential of Boron Neutron Capture Therapy (BNCT) is fundamentally thus linked to Accelerator-Based Neutron Sources (ABNS), which were introduced two decades ago for this purpose to make the paradigm shift which began undergoing clinical use and validation at the Kyoto University Research Reactor Institute by Sumitomo Heavy Industries Ltd, utilizing a cyclotron and a beryllium target. Various types of ABNS, including low-energy electrostatic machines, higher energy cyclotrons, and even more advanced linear accelerators (Linacs) or synchrotrons, have been utilized. Although the neutron beams generated by ABNS exhibit a lower intensity flux in comparison to those produced by nuclear reactors, there is a viable opportunity to achieve the required neutron intensities through multiple accelerator systems. Additionally, ABNS are more compact and cost-effective than traditional nuclear reactors. Radiotherapy departments in hospitals have accumulated significant experience with accelerators over the years. Thus, there is enough scope to initiate such an important healthcare related activity in DAE.

6. Boron Enhancements

A sufficient quantity of boron molecules must be integrated into the tumor cells to facilitate their destruction. To improve the absorption of boron compounds, modifications were made to the infusion method and rate. Various approaches were explored, including intravenous, intra-arterial, and direct infusion into the internal carotid artery **[39]**. Additionally, boron was combined with other agents, such as mannitol **[40]**. Among the methods tested, the most promising approach that has emerged is the use of tumor-targeting moieties along with nanoscale drug delivery systems, specifically utilizing liposomes and nanoparticles **[41-45].**

7. Conclusion and future perspective

Although BNCT has a history spanning several decades, it continues to face challenges that hinder its widespread adoption. Efforts are currently underway by leaders in various fields to address the availability of dependable neutron sources, the development of boron conjugates, and the collaboration among essential stakeholders.

Recent advancements in understanding cancer mechanisms and the identification of various hallmarks of cancer should be incorporated into the development of new strategies and boron compounds. For example, targeting tumor cell metabolism, a recognized hallmark of cancer, has been linked to tumor immunity and offers a potential route for cancer treatment. Regulated cell death plays a critical role in cancer metabolic therapy, and a recent study has identified a novel form of metabolic-related regulated cell death called disulfidptosis. Preliminary results suggest that metabolic therapy using glucose transporter (GLUT) inhibitors can induce disulfidptosis and inhibit cancer proliferation. Boron compounds targeting GLUT1 transporters could potentially enhance the therapeutic effectiveness of Boron Neutron Capture Therapy (BNCT). Additionally, research has shown that inhibiting glucose metabolism triggers a compensatory increase in LAT1, which could improve the uptake of boronophenylalanine (BPA). Combining BPA with these boron compounds may therefore represent a promising strategy to increase boron uptake and improve the therapeutic impact of BNCT. Thus in near future BNCT will be a milestone in the field of radiotherapy for treating cancers.

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Chapter 9: Industrial Radiology: Conventional to computational methods for Non-Destructive Evaluation

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Abstract: *Industrial Radiology (IR), which utilizes radioisotopes and ionizing radiation such as gamma rays, X-rays, and neutron beams, plays a vital role in quality control, defect detection, and structural assessment across various industries through non-destructive evaluation (NDE) of critical materials and components. These technologies not only support industrial growth and enhance productivity but also align with the Department of Atomic Energy's (DAE) mandate for non-power applications of nuclear technology.*

Traditional IR methods—such as gamma radiometry and radiography—are widely employed for tasks including troubleshooting, flaw detection, and corrosion assessment. Gamma radiometry is particularly effective in evaluating shielding integrity and detecting defects in large-scale structures, while radiography provides high-resolution imaging for assessing structural soundness. The application of sealed gamma-emitting radioisotopes for in-situ investigations, along with machine-based X-ray systems for detailed imaging, has further enhanced the capabilities of non-destructive testing.

With the evolution of imaging technologies, IR has transitioned from conventional film-based radiography to digital platforms. Recent advancements in computational imaging have significantly improved efficiency and image quality. Computed Radiography (CR) and Digital Industrial Radiography (DIR) are now industry standards, enabling real-time analysis and superior defect visualization. Building upon these, Industrial Computed Tomography (ICT) offers high-resolution, three-dimensional imaging of internal structures, expanding the scope of industrial applications.

ICT systems employ various geometries—such as parallel beam, fan beam, and cone beam—each suited for specific inspection tasks and offering distinct advantages in resolution and clarity. Core components of ICT, including projection techniques, noise correction strategies, and advanced reconstruction algorithms, are crucial for producing high-fidelity images. Analytical and iterative reconstruction methods enhance defect detectability, particularly in applications such as weld inspection and material integrity evaluation.

As digital and computational imaging technologies continue to advance, industrial radiology remains at the forefront of non-destructive evaluation—driving greater precision, operational efficiency, and reliability in industrial quality control and applied research.

1. Introduction

The use of ionizing radiation in radiology began with the discovery of X-rays in the late 19th century. While initially focused on medical imaging, radiological techniques gradually found applications in industrial sectors as understanding of radiation deepened. This expansion was accelerated by the availability of industrial radioisotopes such as caesium-137, iridium-192, and cobalt-60, which enabled more versatile and powerful radiographic methods [1].

Industrial radiography became integral to Non-Destructive Testing (NDT), particularly in evaluating welds on pressure vessels, pipelines, castings, and forgings. It is also widely used for identifying defects in non-metallic materials, aerospace ceramics, concrete structures, machined parts, and corrosion-prone components. The accurate interpretation of radiographic images in such applications requires highly trained personnel due to the complexity involved [2–4].

In recent years, industrial radiography has undergone a digital transformation. Technologies such as computed radiography (CR) and flat panel detectors (FPDs) have largely replaced conventional film-based methods [5–8]. These digital systems offer higher sensitivity, broader dynamic range, and real-time imaging, making them ideal for online assessments and immediate defect detection [8–11]. CR, with its reusable imaging plates, further reduces environmental impact and operational costs, while improving image quality in specific scenarios [12–14].

Alongside radiography, industrial radiometry plays a critical role in applications such as assessing the thickness and shielding properties of nuclear materials. Its effectiveness depends on the careful selection of radiation sources, detectors, collimators, and calibration techniques. Radiometric assessment of non-circular casks, for example, requires precise and repeated repositioning of the source and detector — a process that is highly sensitive to even slight positional deviations, which can distort beam intensity readings and complicate data interpretation. Ensuring accurate alignment is therefore essential [15].

Over the past decade, Industrial Computed Tomography (ICT) has significantly enhanced inspection capabilities by offering detailed 2D and 3D imaging of internal structures in complex assemblies [16]. Relying on computational reconstruction techniques, ICT supports more comprehensive evaluations, and its applications extend beyond inspection — offering valuable insights for process optimization and quality assurance in allied industries [17].

2. Radiological Investigation Using Sealed Radioisotopes and Radiation

Nuclear radiation sources—both radioisotopic and machine-generated—play a vital role in industrial diagnostics. Radioisotopes are used either in sealed or unsealed forms, with sealed sources being more common in industrial settings. These consist of radioactive material encapsulated in durable containment assemblies fabricated according to ISO 2919 standards. Depending on the application, the activity levels of these sources may range from a few kilobecquerels to several hundred terabecquerels, supporting diverse industrial operations such as thickness gauging, flaw detection, and corrosion monitoring (Table 1). The selection of a suitable source depends on operational needs, test specifications, and commercial considerations (Table 2).

Table 1: Type of industrial radiation installations and typical sources and activity [5]

Radiation installation	Radioisotope sources	Activity (Bq)
Gamma irradiator	^{60}Co	3.3 PBq - 33 PBq
Gamma chambers	^{60}Co	37 TBq - 0.4 PBq
Gamma radiography	^{192}Ir, ^{60}Co, ^{170}Tm, ^{75}Se	370 GBq - 11.1 TBq
Nucleonic gauges	^{241}Am, ^{241}Am-Be, ^{137}Cs, ^{60}Co, ^{85}Kr, ^{90}Sr, ^{147}Pm, ^{55}Fe, ^{109}Cd	185 MBq - 74 GBq
Research studies	^{55}Fe, ^{241}Am-Be, ^{57}Co, ^{241}Am, ^{64}Cu, ^{203}Hg	Few kBq - GBq
Well logging applications	^{241}Am-Be, ^{137}Cs	Few kBq - GBq

Table 2: Application and utilization of radioisotope sources

Industrial	(i) Radiation Processing Plants (RPPs) (ii) Gamma Irradiation Facilities (GIFs)	Industrial radiography and computed tomography	Nucleonic gauge/ Oil well logging/ Gamma scanning of process columns
Research	Sealed and unsealed sources for research studies		

Complementing radioisotopic sources, electrically operated X-ray tubes and high-energy particle accelerators are increasingly used in industrial radiography, especially when flexibility, on-demand operation, and safety are priorities. Source selection in these systems is primarily influenced by material density, specimen thickness, and economic feasibility. For example, conventional X-ray generators (up to 450 kV) are suitable for inspecting steel up to 50 mm thick. In contrast, particle accelerators—such as Van de Graaff generators, betatrons, and linear accelerators (linacs)—are capable of penetrating materials exceeding 150 mm in thickness. Low- to medium-energy accelerators (around 10 MeV, with kilowatt-level power) are commonly used in industrial environments. Additionally, the availability of compact, portable radiographic cameras enhances the feasibility of conducting inspections in field and remote locations.

3. Gamma Radiometry

Gamma radiometry is a key NDT method for defect detection and shielding integrity assessment. Commonly used isotopes include Ir-192 and Co-60, selected for their suitable energy, high radiation output, long half-life, and cost-effectiveness.

A typical radiometry setup involves maintaining a constant source-to-detector distance while measuring transmitted radiation. The intensity follows an exponential attenuation relationship:

$I = I_0\, e^{-(\mu t)}$ (narrow beam geometry) (1)

$I = B\, I_0\, e^{-(\mu t)}$ (broad beam geometry) (2)

Where:

I = Intensity of radiation transmitted through the shielding material at a given distance.

I_0 = Initial radiation intensity measured at the same distance without shielding material.

μ= Linear attenuation coefficient

t = Shielding material thickness

B = Build up factor

A key application of radiometry is verifying the integrity of shielding of vessels and casks employed in nuclear industry. Shielding materials such as lead, concrete, steel, tungsten, or depleted uranium are used to maintain radiation levels within safety standards set by the IAEA and AERB. Any defects in the shielding could increase radiation exposure risks, which is why periodic assessments are essential for ensuring workplace safety.

4. Industrial Conventional Radiography

Radiography is a vital non-destructive testing (NDT) method for assessing internal structures in industries like aerospace, automotive, pipelines, and nuclear components. It detects cracks, flaws, and weld integrity using penetrating ionizing radiation to produce a 2D image of a 3D object. A radiographic setup consists of a radiation source, a detector/film, and an image/film processor (Figure 1). Transmitted intensity varies with material thickness and density, creating contrast in the image. In film-based radiography, silver halide film captures transmitted radiation, allowing detection of defects with different source-film combinations.

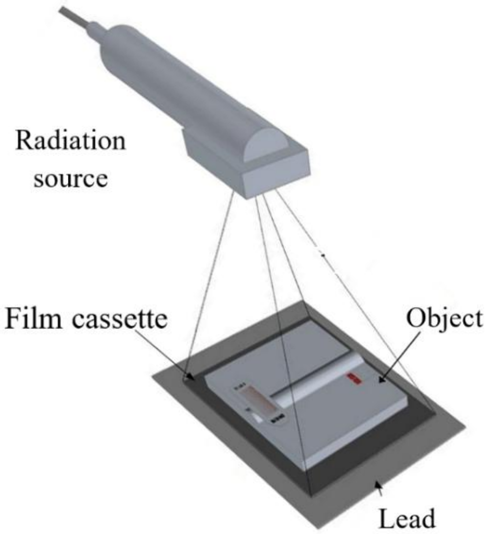

Figure 1. Typical industrial conventional radiography setup

4.1 Radiographic film:

Radiographic film consists of layers shown in figure-2 and detailed below.

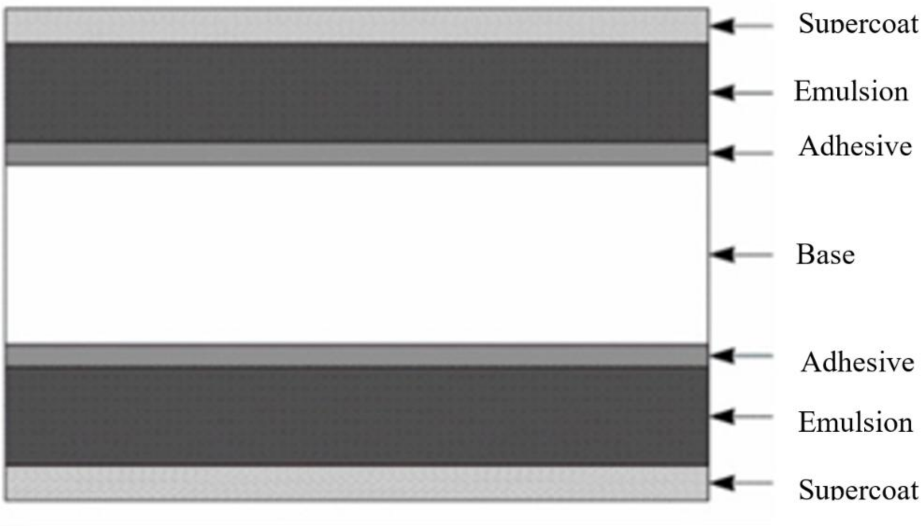

Figure 2. Cross-section of a radiographic film

Base: Strong, flexible, transparent polyester (preferred over triacetate).
Emulsion: Silver bromide in gelatin, forming the sensitive layer.
Subbing Layer: Ensures adhesion between base and emulsion.
Super-coat: Protective outer layer.
When exposed to radiation, the emulsion captures a latent image, which is then developed into visible shades of gray. As exposure increases, the optical density also rises, effectively revealing internal defects with better contrast.

5. Computed Radiography

Computed Radiography (CR) utilizes phosphor image plates as the recording medium to capture the transmitted radiation beam after it passes through the object under examination. Similar to traditional chemical-based films, CR image plates store a latent image—a matrix of trapped electrons formed when X-ray quanta are absorbed by the plate's atoms, without any immediate visual change. Figure-3 shows a schematic representation of computed radiographic set-up.

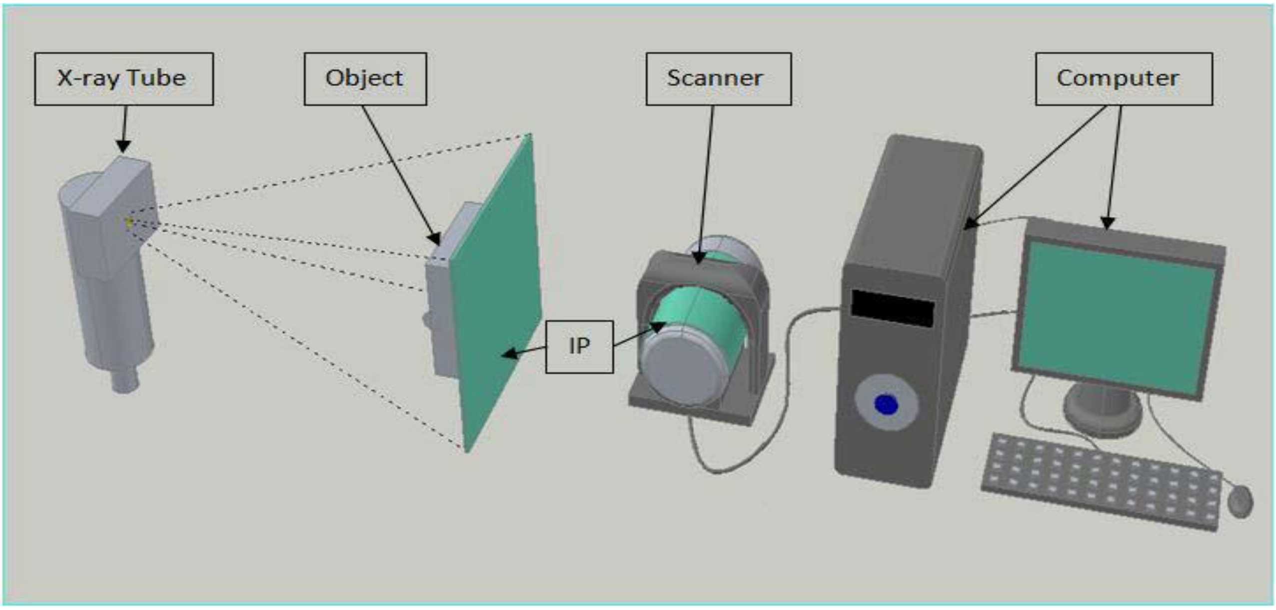

Figure 3: Typical Experimental Setup for the computed radiography

A CR image plate consists of a flexible polymer-based thin sheet coated with a photo-stimulable phosphor (PSP) layer, which is protected by a thin coating to prevent mechanical damage. After exposure to radiation, the plate is scanned using a helium-neon (He-Ne) laser, causing the stored energy to be released as blue light—a process known as photo-stimulable luminescence. This emitted light is detected by a photomultiplier tube (PMT) or a solid-state detector, where its intensity correlates with the radiographic density at each point. The detected signal is electronically converted into digital values, forming an image file for further processing. To prepare the plate for reuse, the latent image is erased by scanning with white light, allowing repeated exposures.

The acquired image is then processed and enhanced using image processing techniques before evaluation. The sensitivity and spatial resolution of the system depend on factors such as phosphor layer thickness, scanner quality, and laser focal spot size. Typically, scanning is optimized with a 100 µm spot size for 'fast' image plates, while 'standard' plates use a 50 µm spot size. For high-resolution applications, a 'high-definition' image plate with a 20 µm pixel size is employed, ensuring greater detail in radiographic analysis.

6. Digital Industrial Radiography

DIR works on the principle of conversion of incoming radiation into appropriate signal using electronic circuit. It involves array of radiation sensitive material and associated signal processing systems. These arrays are popularly known as Flat panel detectors (FPD). FPDs are two-dimensional arrays of small solid-state sensors. These sensors can capture X-ray or gamma-ray photons and convert them into charges that can be electronically measured. The entire apparatus is built on a glass substrate and housed within a durable metal frame to protect it from physical damage. The clarity of the resulting image depends on the size of the sensors in the array. The digital output from the sensor array is transmitted to a computer through a fast data acquisition system. This system collects data correlating to the radiation exposure of the device, enabling the radiographic image to be displayed almost immediately for analysis.

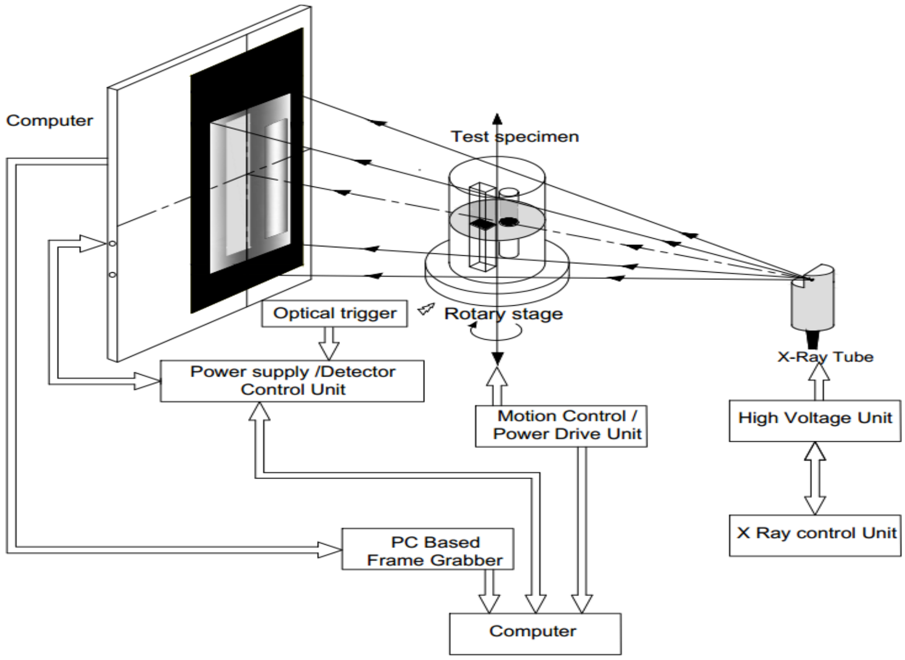

Figure 4. Schematic representation of a typical X-ray based DR&CT setup

FPDs are available in two main types: Indirect conversion and direct conversion. Indirect conversion FPDs feature a scintillating material layer (such as Gd_2O_2S:Tb, CsI) at the forefront. This layer transforms incoming X-rays into visible light, which is then detected by a series of photodiodes. The photodiodes change this light into electrical charges, powering the TFTs embedded in a layer of amorphous silicon. The resolution in these devices not only depends on the pixel size but also on the type of scintillating material used and the level of optical cross-talk in the scintillator. The intensity of the signal from an indirect conversion FPD is proportional to the amount of light generated by the scintillation process. Direct conversion FPDs utilize amorphous selenium to absorb X-ray photons and directly generate charge carriers (electron-hole pairs), eliminating the need for an additional scintillator layer. Each pixel in this system incorporates thin film transistors (TFT) and a storage capacitor, integral to the detector structure. However, direct conversion FPDs typically have a limited energy range, suitable for X-rays up to about 50 keV. Figure 4 shows the schematic of a X ray-based DR &CT set-up.

7. Industrial Computed Tomography

Industrial Computed Tomography (ICT), unlike basic projection radiography, is an indirect imaging method. At its core, tomography involves reconstructing cross-sectional images that represent slices of a volumetric object being examined. This process of reconstructing the desired parameters from tomography requires extensive computational effort based on the data collected externally. Though often associated with medical applications, computed tomography has increasingly found use in various industrial settings due to its non-invasive imaging capabilities. Industrial CT is a sophisticated method in Non-Destructive Testing and Evaluation (NDT&E), utilized across physics, material science, and other scientific and engineering disciplines. There are three primary techniques employed in Industrial CT systems, differentiated by the geometry of the X-ray beam acquisition: parallel beam, fan beam, and cone beam. Each geometry type has unique benefits and is tailored for particular applications in industrial imaging and inspection tasks. Figure 5 shows a typical volume CT analysis software interface.

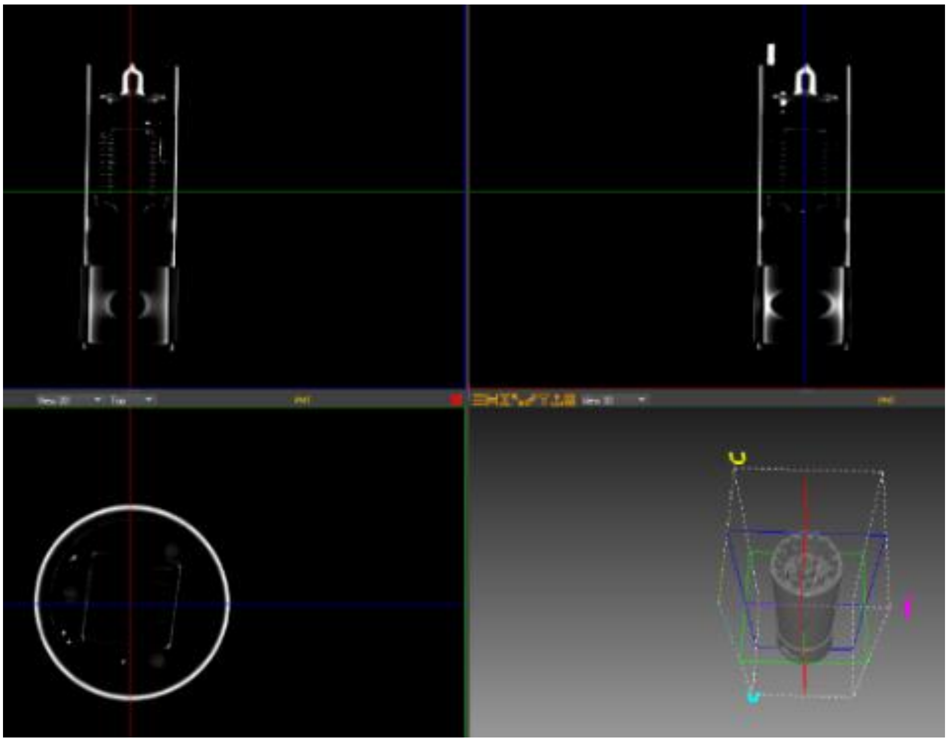

Figure 5. Visualization and interpretation software

Figure 6. Picture showing radiometric testing of shielded hot cells in a radiopharmaceutical laboratory under construction. The radioactive source is kept inside the shielded cell

8. Selected case studies (CS)

CS-1: Figure 6 shows radiometric testing of shielded hot cells in a radiopharmaceutical laboratory under construction. The plant contains both flat and cylindrical components of radiation shielding materials. Experiments were carried out by keeping the source at the center of the job and transmitted dose rate was measured around the outer surface. Main challenge in radiometry comes from object's geometry. In industry, geometry of the shielding arrangement varies from case-to-case basis. Therefore, every object with specific geometry, requires a specific approach of testing.

CS-2: Failure analysis is essential to assess internal condition of the component. Weld samples were investigated for failure analysis nondestructively using radiographic method. The RT experiments were performed using a constant potential X-ray generator (40-450 kV) having 0.4 mm focal spot size and source-to-detector distance was approximately one meter. The weld joint section is between carbon steel pipe A333 grade 6 and carbon steel flange of a facility involved in production of heavy water. Experimental setup, photograph and radiograph of the weld coupons are shown in the figure 7. The results of radiologic examination show that the contrast sensitivity of about 2.0% has been achieved. Flaw analysis revealed crack, lack of penetration (LOP) and porosity.

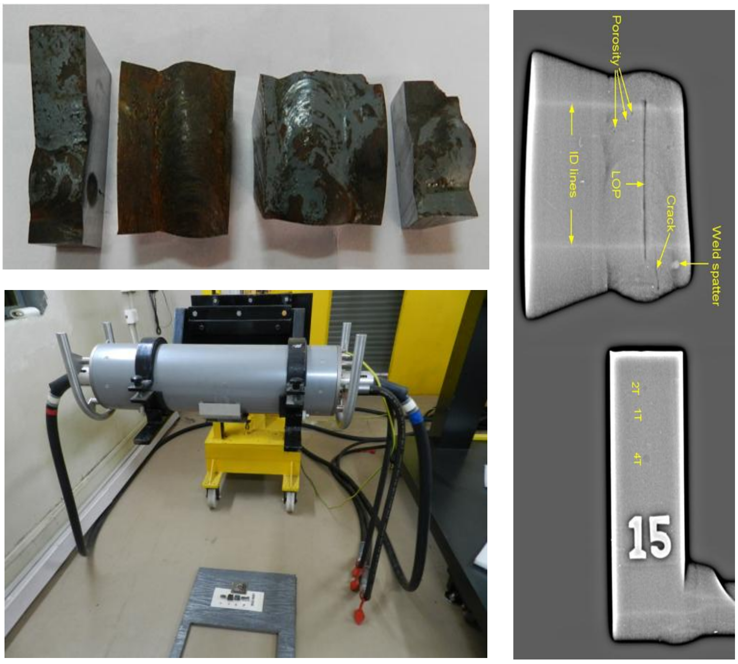

Figure 7. Photograph of weld specimen (top left), RT experimental setup (bottom left) and radiographic image revealing weld defects(right)

CS-3: An experimental study is presented here to demonstrate both qualitative and quantitative evaluations possible using ICT imaging. A cylindrical phantom embedded with blades were reconstructed in cone beam CT modality. The qualitative analysis involved visual assessments by experienced radiologists who examined the clarity, contrast, and delineation of the blades within the cylinder. Quantitative analysis was based on specific metrics such as SNR, and artifact presence, which were calculated from the image data and presented in table 3. Figure 8 shows some of the results including 3D images built using CT slices.

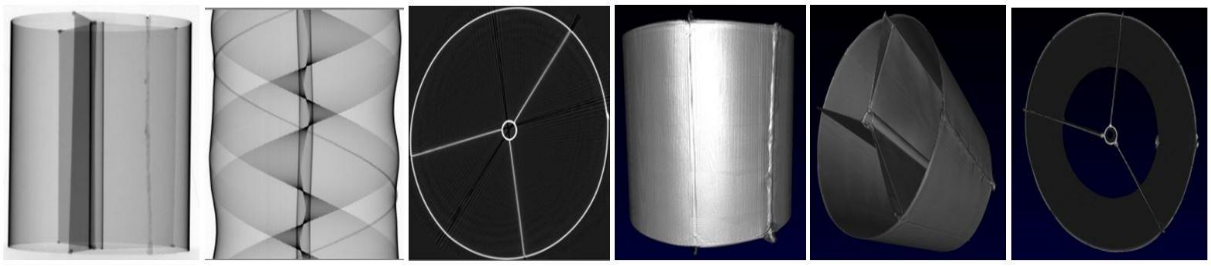

Figure 8. Step-by-step scan from left to right Radiograph, Sinogram, Tomograph, 3D front view, 3D inclined view, 3D top view

Table 3. Quantitative analysis CBCT images

Line Profile					Area measurement					
Min	**Max**	**Median**	**Mean**	**Standard deviation**	**Min**	**Max**	**Median**	**Mean**	**Standard deviation**	**SNR**
68	138	84	88.37	15.67	62	95	83	81.13	6.178	14.4

9. Conclusion

Conventional radiometric and radiographic techniques using sealed radioisotopes and radiation have been essential in non-destructive testing and evaluation (NDT&E) for quality control of critical components, assemblies, and structures. Over the past few decades, Bhabha Atomic Research Centre (BARC) has made significant strides in advancing and promoting these industrial radiology techniques. In parallel with technological progress, BARC has also focused on human resource development through Radiography Testing Level-1 (RT-1) and Level-2 (RT-2) training programs, ensuring a skilled workforce for the nation. These combined efforts have strengthened industrial growth, enhanced productivity, and supported self-reliance in key sectors.

The evolution from conventional radiography to advanced computational imaging has further transformed industrial inspection processes. Digital Industrial Radiography (DIR) and Industrial Computed Tomography (ICT) have enhanced efficiency, accuracy, and versatility in defect detection and structural assessment. ICT, in particular, has become a cornerstone in NDT&E, offering high-resolution internal imaging with various beam geometries and sophisticated reconstruction algorithms. The transition from analytical to iterative reconstruction methods has significantly improved image quality and computational efficiency, optimizing industrial applications.

The integration of advanced detector systems, precise mechanical manipulators, and robust data acquisition has expanded ICT's capabilities, making it invaluable for high-precision inspections. Transportable ICT systems are opening new possibilities for on-site industrial applications, providing flexibility for varied operational environments. Case studies further demonstrate the practical impact of these techniques in ensuring product integrity and safety across industries.

As industrial demands evolve, the future of radiological imaging looks promising, with ongoing innovations poised to refine these techniques further. Embracing these advancements will not only enhance industrial outcomes but also drive continuous progress in computational imaging, reinforcing its indispensable role in modern industrial practices.

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Chapter 10: Societal and Industrial Applications of Thermal Neutron Imaging

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Abstract: *Neutron imaging is a non-destructive technique that can reveal the interior of many materials and engineering components, yielding both 2D and 3D information about the material. Neutron radiography and neutron tomography are widely used for research as well as societal and industrial applications. Advanced Neutron Imaging Facility at Dhruva reactor caters to various neutron imaging applications – both for in-house research as well as external users and industry. This paper presents the basic concept of neutron imaging, and discusses few societal and industrial applications carried out at the facility.*

1. Introduction

Neutron imaging [1, 2] is a powerful tool for non-destructive testing of materials and finds numerous applications in industry and in material research as well. Conventional neutron imaging is based on absorption contrast wherein a neutron beam passing through an object undergoes loss in intensity due to absorption or scattering and the transmitted neutron intensity is recorded by a detector to provide spatially resolved image. Neutrons interact with the nuclei of the atoms that compose the sample and the absorption and scattering properties of the contained elements make it possible to produce images of components containing light elements, like hydrogen beneath a matrix of metallic elements, (like lead or iron), which cannot be easily done with conventional X ray radiography. X-rays are good for distinguishing high Z materials whereas (thermal) neutrons show higher attenuation and thereby higher contrast in low Z materials.

Exploiting this property, neutron imaging has been used in applications requiring the identification of low Z materials inside solid metallic samples. Although traditional transmission radiography still plays an important role, development of more sophisticated techniques like tomography, phase contrast radiography and tomography, real-time imaging of systems including fluid flow and/or moving components, energy selective inspection have widened the scope of neutron imaging. Strong neutron sources like research reactors and accelerator-based spallation neutron sources can provide intense neutron beams, required for efficient and practical neutron imaging. Such beams have been successfully used for neutron radiography during the last two decades. Neutron radiography has found its greatest applications in the examination of nuclear fuels [3, 4], engine turbines blades, and material characterization [5]. Recently, neutron imaging has been used in new branches: fuel cell research, archaeological artefacts, geo-science, paleontology [6] etc.

Neutron imaging techniques - both radiography (2D) and tomography (3D) - have many societal applications also in various fields including non-destructive testing in manufacturing, quality control in industries like aerospace and automotive, analyzing cultural heritage artifacts [7] and studying biological samples and agriculture applications [8,9].

2. Neutron Tomography

Neutron beam transmitted through an object is recorded by a planar (2D) detector, i.e. the detector records a two-dimensional image that is a projection of the object on the detector plane. This image is known as a radiograph (Fig. 1). The features that lie along the direction of propagation of the beam are integrated in the projection image and cannot be distinguished in a radiograph.

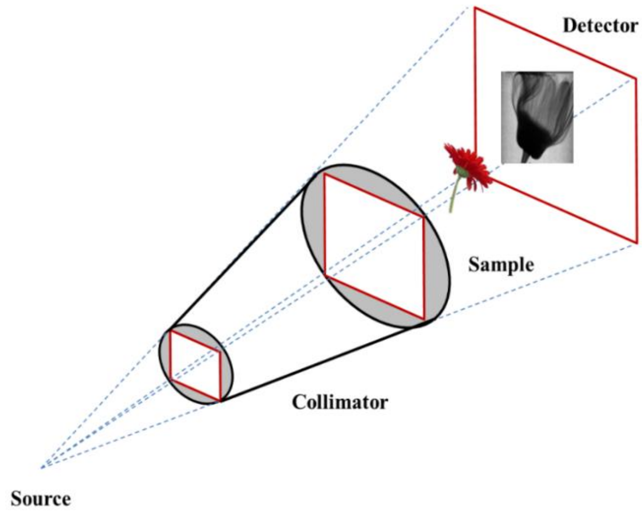

Figure 1. Schematic of Neutron Radiography set-up [1]

Tomography (or Computed Tomography) is a method to acquire three-dimensional information about the structure inside a sample. It uses radiographic projection images from many views to reconstruct the distribution of materials in the sample. Mostly, the projections are acquired with equiangular steps over either 180° or 360° to cover the whole sample. Figure 2 shows an experimental set-up used for neutron tomography. The transformation of the projection data into a three-dimensional image is a computationally intensive task handled by special reconstruction software. During the reconstruction process, slices perpendicular to the rotation axis are produced. When these slices are stacked in a sequence they form a three-dimensional volume image of the sample. This can be used to reveal details (cross-sectional information) inside the sample in three dimensions.

3. Advanced Neutron Imaging Facility at Dhruva Reactor

Advanced Neutron Imaging Facility [10] at HS-3018 beamport of Dhruva reactor is a state-of-art thermal neutron imaging beamline which caters to both DAE and non-DAE users as well as industrial users. Table 1 tabulates the main features of the beamline. Some of the important studies carried out at this facility include hydrogen ingression studies in zircaloy pressure tubes, secondary hydriding in fuel clad under simulated loss-of-coolant accident (LOCA) conditions, cracks in failed turbine blades, real-time investigation of lead melting, examining welds in materials, study of pyrotechnic devices for space applications, water transport in plant roots, archaeological artefacts like metal statues, weapons and coins, palaeontology fossils, etc.

Table 1: Features of Advanced Neutron Imaging Facility

Parameters	Value
Thermal Neutron Flux	4×10^7 n/s-cm^2
Beam diameter	100 mm
Cadmium Ratio	250
Collimation Ratio (L/d)	160
Spatial Resolution	~ 100 µm
Detectors available	^{6}LiF:ZnS(Ag) + CCD ^{6}LiF:ZnS(Ag) + sCMOS Image Plate (IP)
Imaging modes	Neutron Radiography Neutron Tomography Dynamic Neutron Radiography Neutron Phase Contrast Imaging

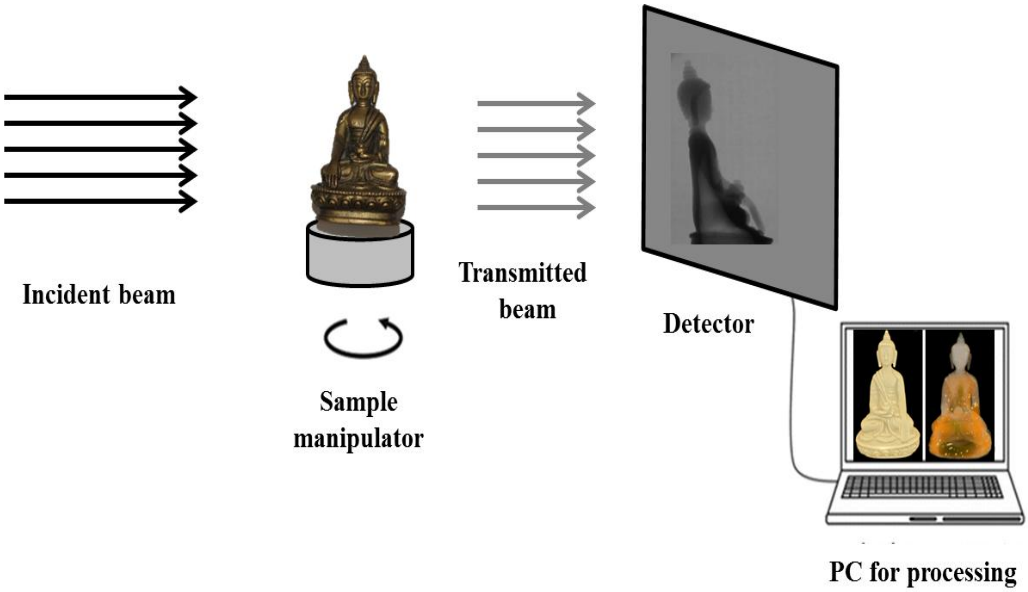

Figure 2. Schematic of Neutron Tomography set-up [1]

4. Applications in Archaeology and Cultural Heritage

Neutron imaging can be used for investigation and analysis of many aspects of cultural heritage and preservation –from museum artifacts and metallic statues to scrolls and ancient manuscripts, and archaeological findings. Neutron Tomography can be applied to characterize archaeological and cultural heritage items to obtain detailed data regarding the assembly/features of inner parts of artifacts, the evolution of cracks and defects, which can shed light on the manufacturing techniques or processes developed by different cultures over time. Its capacity to extract detailed information about the internal structure of an object has significant ramifications for archaeological conservation, enabling the development of more targeted approaches to treatment and monitoring and assessment of the treatments applied.

4.1 Tomography of Metal Artefacts

Thermal neutrons can easily penetrate few centimetres of metal objects and are sensitive to hydrogenous substances. The non-destructive investigation of metallic cultural heritage objects like bronze or brass sculptures, coins and weapons by neutron based methods provides very impressive results.

Figure 3(a) shows photograph of a bronze Buddha statue which was casted using lost-wax technique. Figures 3(b) and 3(c) show neutron radiograph at different orientations of the statue. Figure 3(d) and 3(e) show reconstructed 3D volume generated using neutron tomography. The opacity in the 3D volume has been reduced in Fig. 3(e) to reveal wax remnants just beneath the surface of the statue

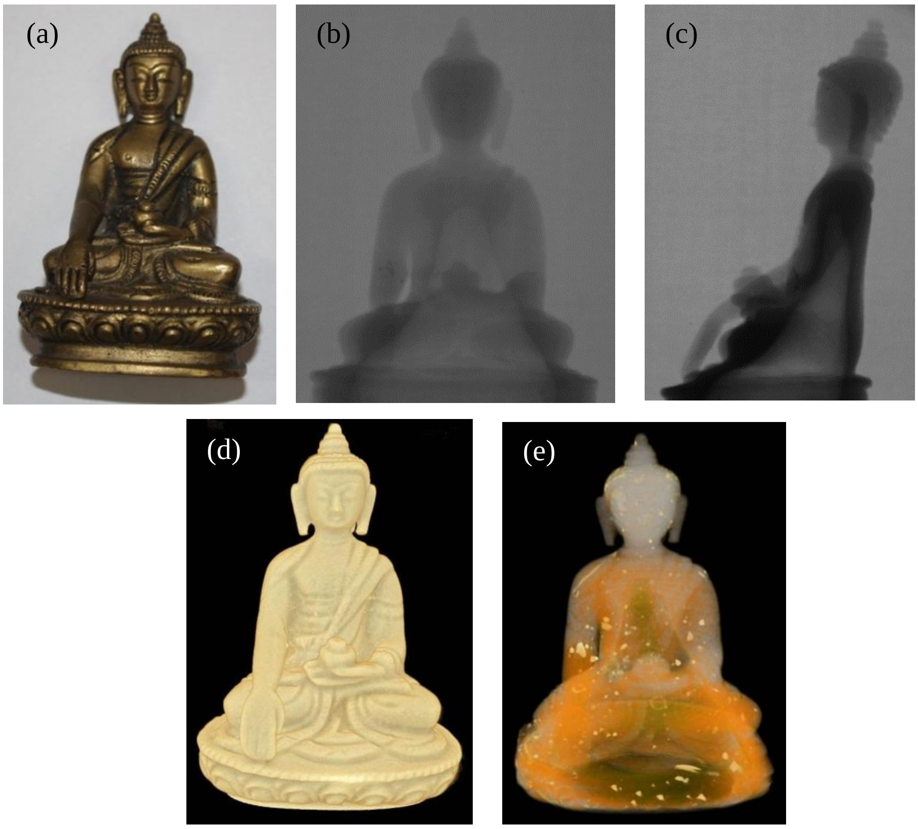

Figure 3. Bronze Buddha statue (a) Photograph (b), (c) Neutron Radiograph (d), (e) Reconstructed 3D volume using Neutron tomography

Figures 4(a) and 4(e) show 17th-century archaeological solid brass statues of tribal woman and tribal man respectively. Figures 4(b) and 4(f) show the neutron radiography and Figs. 4(c, d) and 4(g, h) show neutron tomography images of the tribal woman and tribal man statues respectively.

An interesting feature revealed in the tomography scan is the sizable tubular cavity with a well-defined shape in the lower abdomen region of the tribal woman statue resembling female reproductive part hinting that the statue might have represented a Goddess of fertility or a Mother Earth-like deity. Fig. 4(d) shows a vertical cut section of the statuette, highlighting the tubular structure in the abdomen region. Similarly, a low-density metallic region is observed in the abdomen region of the tribal man statue (see Fig. 4(g)). Also, some spiral indentations resembling a belt or waistband like structure with higher attenuation are observed. The structures and the non-uniform metallic region in the abdomen are highlighted in the cut-section views shown in Fig. 4(h)

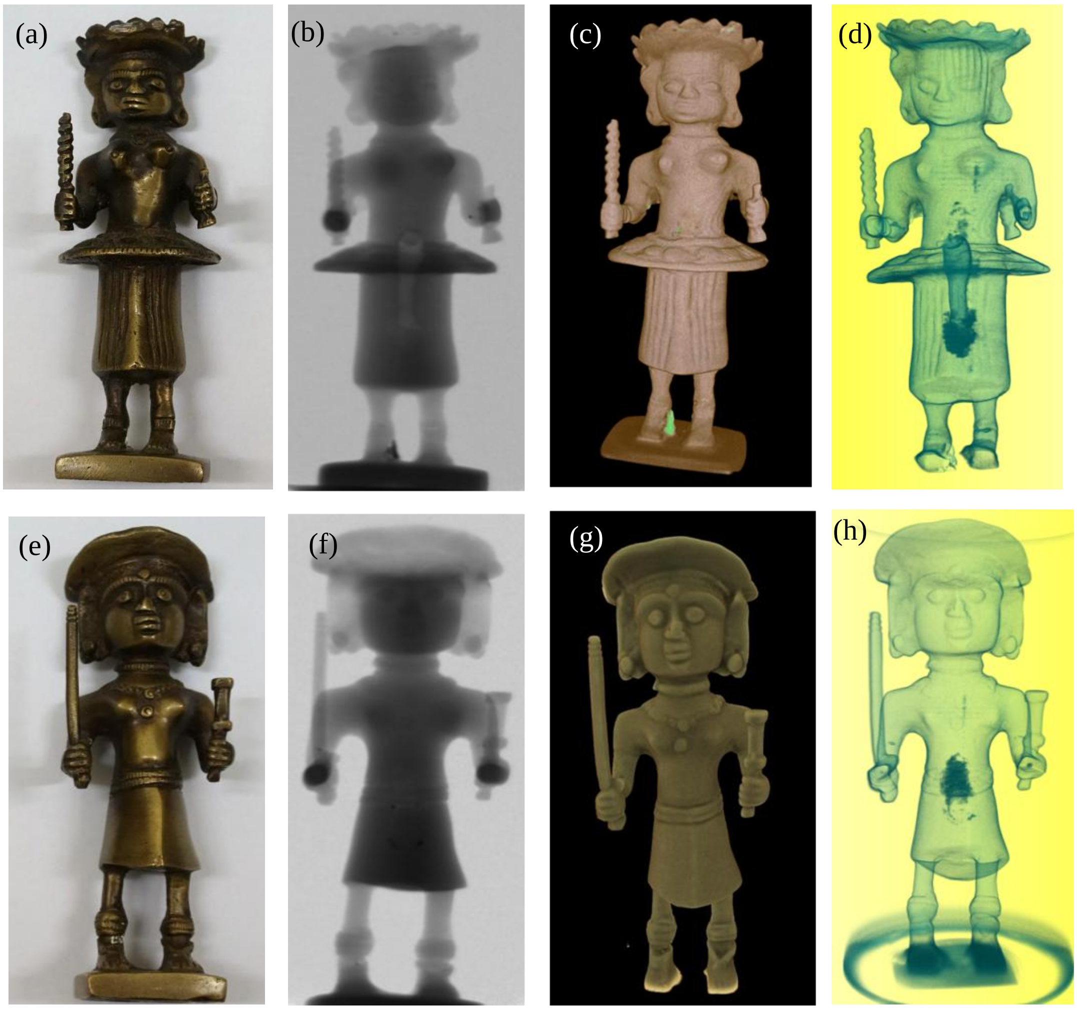

Figure 4. Brass statues of Tribal woman (top row) and Tribal man (bottom row) (a), (e) Photograph (b), (f) Neutron Radiograph (c), (d), (g), (h) Reconstructed 3D volume using Neutron tomography [7]

An iron *Kataar* (short dagger) (Fig. 5(a)) from the Maratha empire was studied using Neutron radiography. Figure 5(b) shows the neutron radiograph of the *Kataar* including the blade and hilt. It is observed that the metal on the bottom portion of the blade as well as the edge has undergone corrosion and the tip of the blade is rather blunt due to usage.

Figures 6(a) and 6(b) show the obverse and reverse faces of a copper coin. Figures 6(c) and 6(d) show the neutron tomography view of both the faces of the coin and the symbols and patterns engraved on the coin surface can be easily observed. The tomography also shows a layer of patina (Fig. 6(e)) covering the coin surface. The eroding of the metallic coin is also visible at few places on the surface.

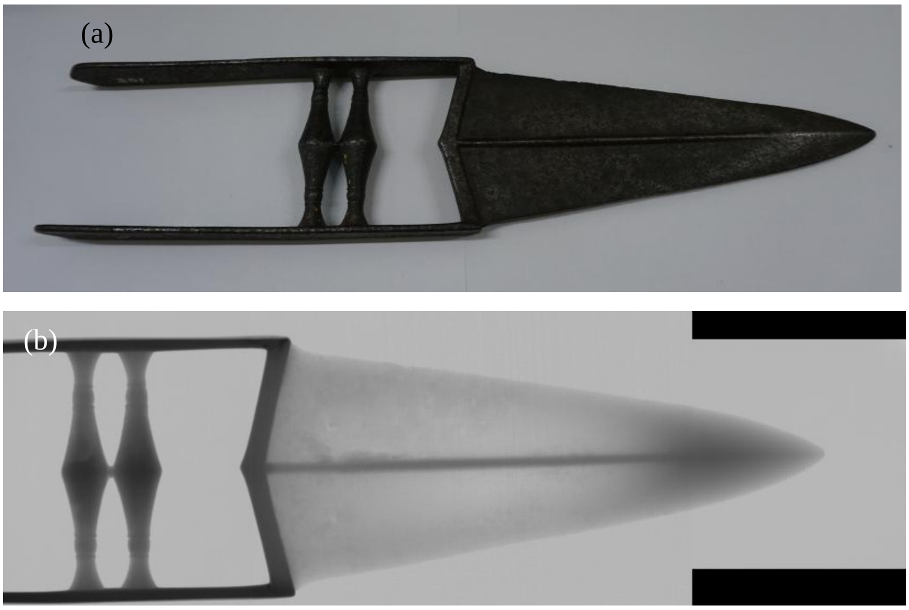

Figure 5. *Kataar* (short dagger) of the Marathas (a) Photograph (b) Neutron Radiograph

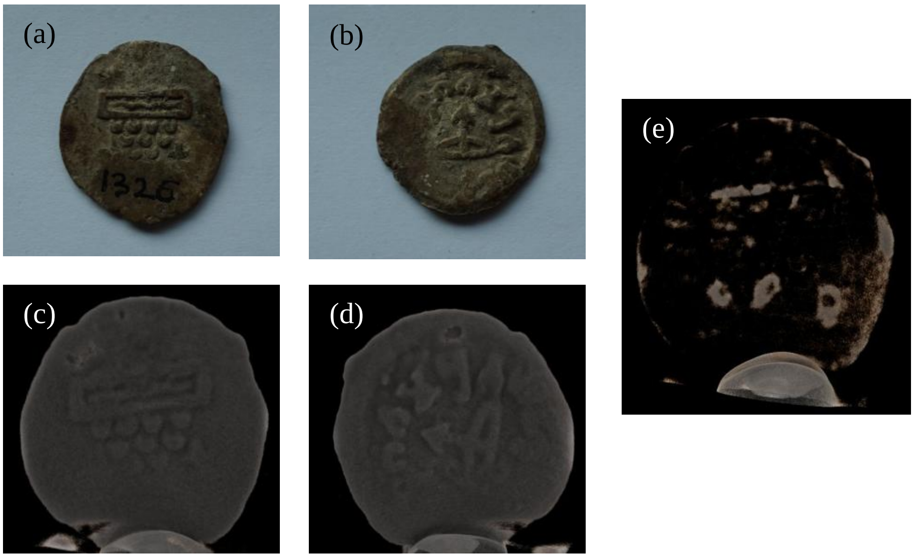

Figure 6. Copper coin (a), (b) Photograph (c), (d) Neutron Tomograph (e) Highlighting the patina formation on the coin surface

5. Applications in Palaeontology

Fossils are formed when minerals such as calcium carbonate, over time, envelope and/or replace bones and other organic matter. The covering hardens and casts them into the rock matrix which remains untouched and thus unchanged for millions of years. Fossils usually represent the hard parts, such as bones or shells of animals and leaves, seeds, or woody parts of plants. Neutron radiography is a modern, unique, non-invasive and non-destructive analytic technique which can be used to study fossils. Neutrons are sensitive to detect small differences in the concentration of some light materials such as hydrogen. Also, neutrons have a high penetration and can be used to study fossilized rocks and geological samples. 3-D visualization and characterization of internal structures of vertebrate in fossils is a much sought after ability of neutrons.

Neutron Tomography studies were carried out on geological sample from Jaisalmer river bed (Bandah Formation of middle Eocene age). The samples analyzed are bundles of boring produced by the xylophagous (organisms that live on woody substrates) bivalves, also called shipworms, belonging to the family *Teredinidae*. They have been observed within present and fossilized substrate of accumulated woods as well as in individual allochthones fossilized logs that were transported as detrital sediments in water. Distribution of modern *Teredinidae* is controlled by the factors such as temperature, salinity, and presence of substrate. The availability of wood fragment as substrate also plays an important role and is directly related to the cyclic relative sea-level fluctuations. These studies are important to reveal the transgressive-regressive relative sea-level cycles of the ancient seaway that existed in western Rajasthan and the relation of these wood-boring organisms with respect to the changing sea. Figure 7(a) shows the neutron radiograph. Figures 7(b) and 7(c) show the morphological details of the sample in the 3D volume generated using neutron tomography.

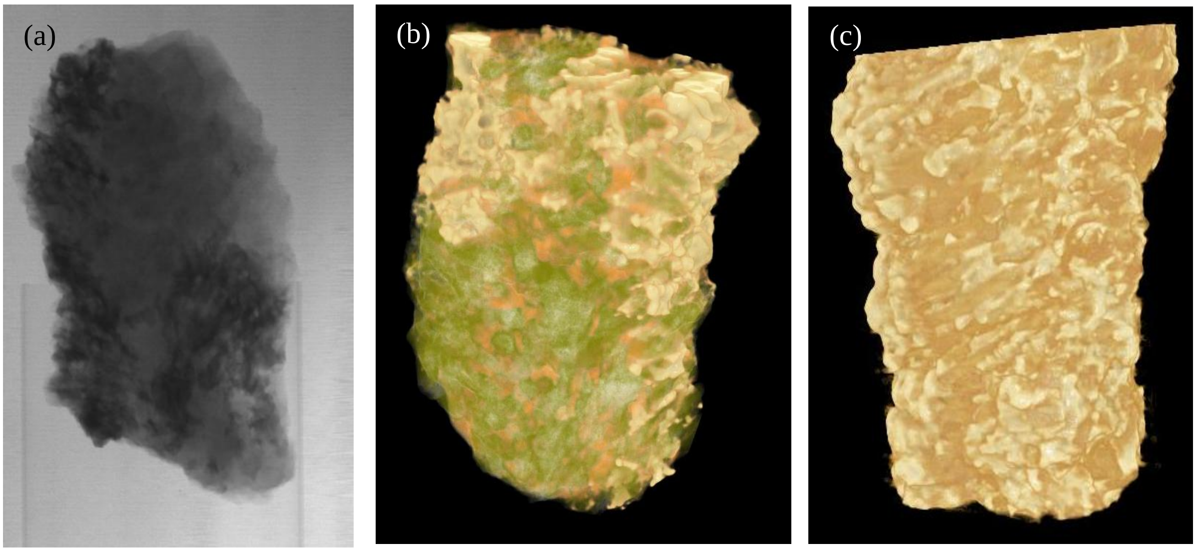

Figure 7. Geological samples from Jaisalmer river bed (a) Neutron Radiograph (b), (c) 3D volume generated using Neutron Tomography

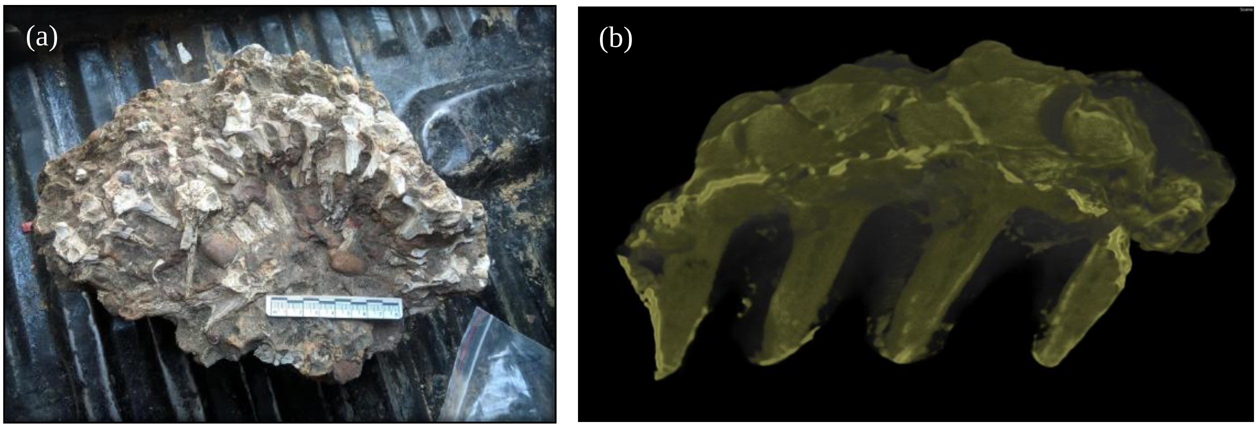

Figure 8. A part of the fossilized remains of Giant Marine Snake *Pterosphenus schucherti* (a) Photograph (b) 3D volume generated using Neutron Tomography [6]

Neutron Tomography studies were carried out on fossil remains collected from the limestone bed of the Harudi Formation in the Kuchchh Basin by the Ichnology group (Bombay Ichnos Research Group) of the Department of Earth Sciences, IIT Bombay. Neutron Tomography scan of the prepared fossil was conducted at BARC on different sections of the fossil. Figure 8(a) shows photograph of a part of the fossilized remains of the giant marine snake. Figure 8(b) shows the 3D volume generated using neutron tomography highlighting the vertebrae structure of the snake. The discovery of an articulated section of the large snake *Pterosphenus schucherti* from the Bartonian-aged Harudi Formation fills an important gap in our understanding of these enigmatic snakes. The articulated section records crucial information of intra-columnar variation in the species. This study led to the taxonomic revision of two previously described species, *Pterosphenus schewinfurthi* and *Pterosphenus biswasi* with the *Pterosphenus schucherti* species.

6. Applications in Agriculture

Neutron imaging is ideal for agricultural research applications because neutrons are sensitive to hydrogen, which the plants / roots contain in abundance. In contrast, the soil does not contain a lot of hydrogen. That means the plant roots show up as dark, clear, and distinct regions in the radiographic images. Neutrons are ideally suited for this task since they readily penetrate most common materials but are strongly attenuated by those containing hydrogen such as water. Root architecture, root growth and soil and plant water distribution are thus readily imaged and quantified using neutron imaging.

Exopolysaccharides (EPS) are organic macromolecules naturally secreted by many microorganisms. EPS is increasingly used for agriculture and industrial purposes. A study was carried out to explore water retention efficiency of EPS producing rhizobacteria under drought conditions. Neutron Radiography was used to visualize and quantify water distribution in soil under normal and drought conditions in the presence and absence of EPS producing bacteria. For the experiments, soil columns were prepared in three identical cuvettes (10 mm × 10 mm × 50 mm) with finely sieved sterile sandy soil samples. 1 ml of water was added uniformly to the control sample. For the remaining two samples, 0.5 ml of water and 0.5 ml of EPS broth of two different strains of EPS producing rhizobacteria AZ and SG2 were added respectively. All three saturated soil columns were placed in a row and exposed to the neutron beam for radiography. All samples were imaged simultaneously to ensure the same environmental conditions. A series of individual radiographs were acquired over a total duration of approximately 17 hours. The drying out progression of soil columns is shown in Figure 9 where blue colour indicates higher concentration of water.

The Relative Water Content (RWC) of EPS treated soils was also evaluated and it shows higher water retention capacity compared to the control sample. After 17 hours of evaporation, the RWC of the EPS sample was approximately 55% whereas for control sample was approximately 12% as indicated in Fig. 10.

7. Industrial Applications

Neutron imaging plays a major role in non-destructive testing in manufacturing industry such as detecting internal flaws in metal components like turbine blades in aircraft engines, identifying corrosion in machinery, and inspecting welds without damaging the material. In the aerospace sector, neutron imaging has become vitally important. Various critical components used in aircraft and spacecraft such as turbine blades must be carefully tested to meet the optimal design standards as any flaw or defect in the samples is unacceptable. Neutron Radiography (NR) has become a mandatory inspection technique for aerospace applications in the recent years.

Turbine blades are cast in ceramic moulds out of strong and lightweight metal, such as Ti-Al alloys, that has a melting point lower than the operating temperature of the engine. The turbine blades need to be properly cooled as they are subjected to lot of heat and stress. Flaw in them might result in engine failure and potentially lead to plane crash and loss of life. Hence, turbine blades have to undergo rigorous quality checks due to their high cost of failure.

Neutron imaging is an effective and reliable NDT method for detecting low Z elements which in this case are ceramic remnants in turbine blades. It is superior to X-ray imaging due to its high contrast in neutron attenuations between ceramic remnants and the blade. Figures 11(a) and 11(b) show neutron radiograph and neutron tomography of a turbine blade respectively. The internal structures can be easily observed.

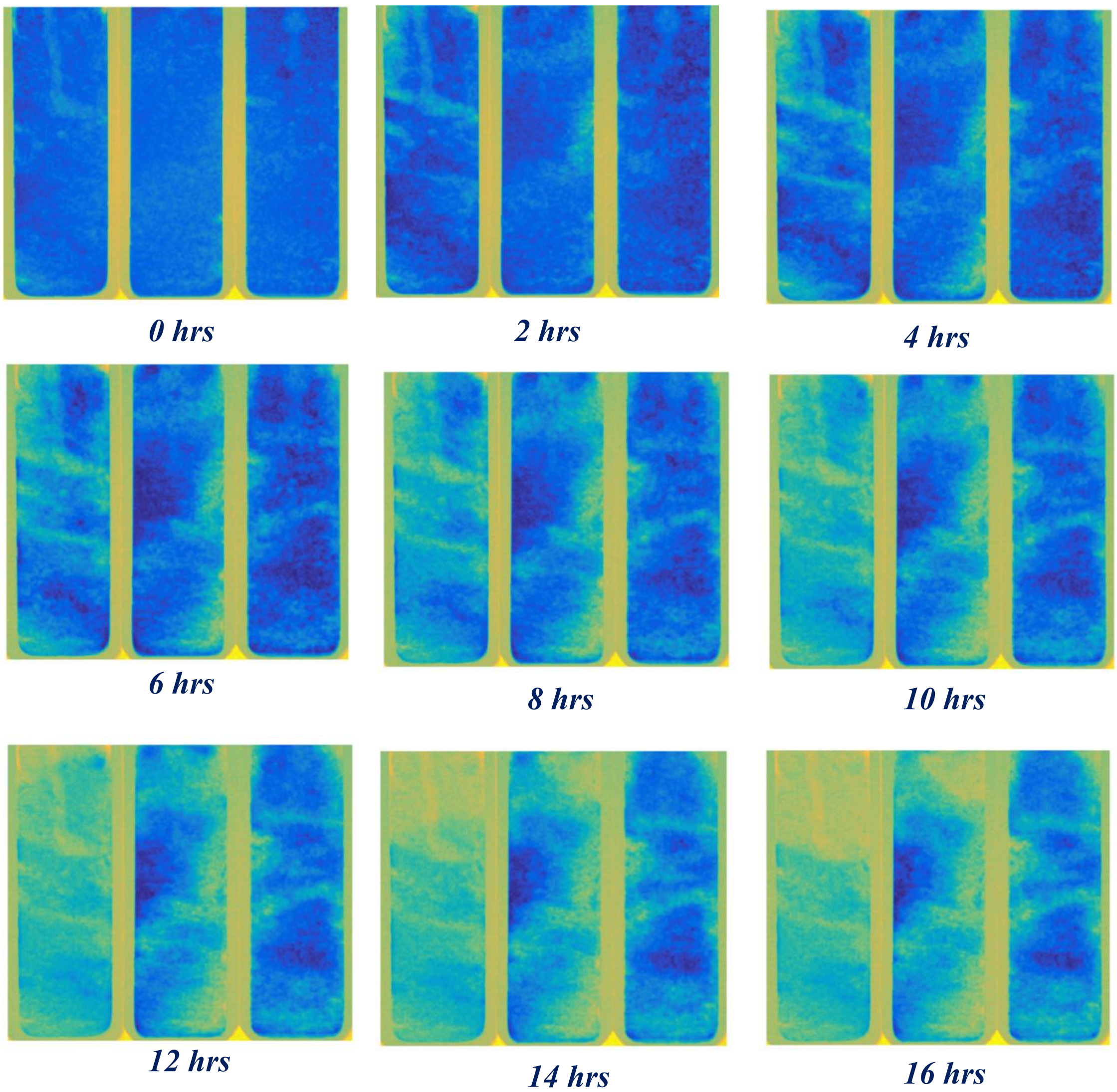

Figure 9. Drying-out progression—Neutron radiographs at different time intervals after addition of water at time t=0. In each set of images, the samples are arranged as (from left to right) control (water), AZ and SG2 strains

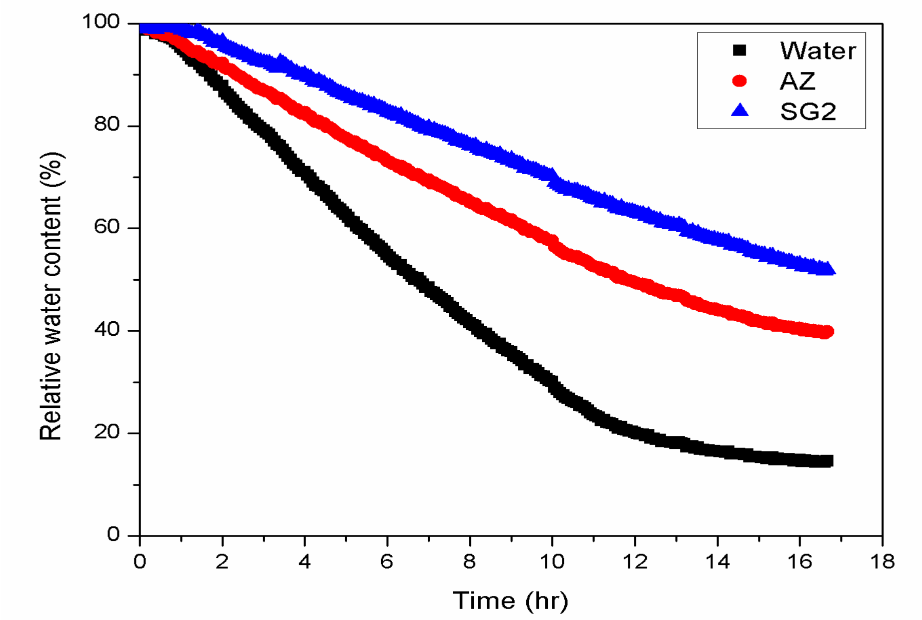

Figure 10. Relative water content during evaporation as a function of time

8. Summary

Neutron radiography and neutron tomography techniques have established themselves as invaluable non-destructive inspection methods and quantitative measurement tools. Neutron imaging also plays an important role for societal and industrial applications. This paper gave a glimpse of various societal and industrial applications of neutron imaging activities carried out at Advanced Neutron Imaging Facility at Dhruva, BARC.

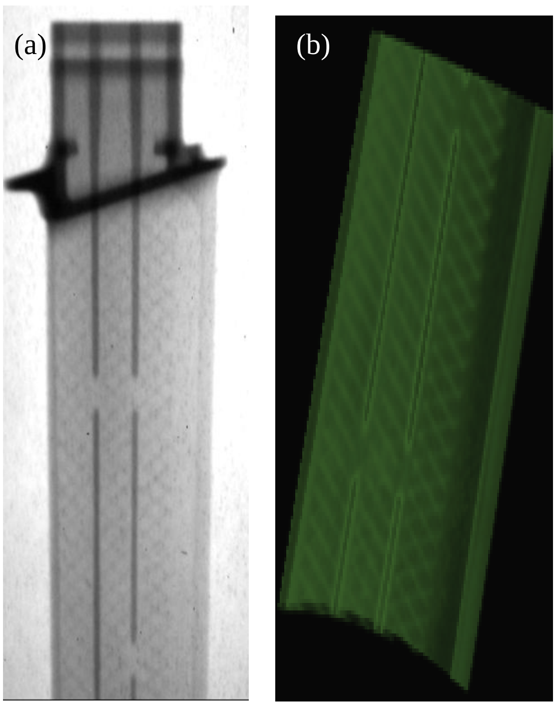

Figure 11. (a) Neutron Radiograph and (b) Neutron tomograph of turbine

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Dr. Shefali Shukla, joined BARC in 2013 as a Scientific Officer after completing her Masters in Physics. She did her Ph.D. in the field of Neutron Imaging applications and is currently working in the Technical Physics Division. Her technical expertise includes neutron radiography and tomography applications particularly hydrogen estimation in metals using neutron imaging.

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Chapter 11: BARC-DAE Technologies for Industry & Society

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Abstract: *Technology Transfer & Collaboration Division (TT&CD), DAE is responsible for evaluation, publishing and transfer of spin-off technologies developed in all units of DAE located all over India to the industry. The major activities of TT&CD can be segmented into four broad domains: (a) Technology publishing and transfer, (b) Consultancy services, collaboration and patent, (c) Atal Incubation Centre (AIC) and (d) Advanced Knowledge and RUrban Technology Implementation initiative (AKRUTI). The four subsequent sections below are to briefly pronounce the notable activities and achievements during the last year. Technologies available for transfer are published on BARC's website for advertisement. More than 220 technologies from different fields are available for commercialization which are grouped into following eight groups.*

1. Technology publishing and transfer

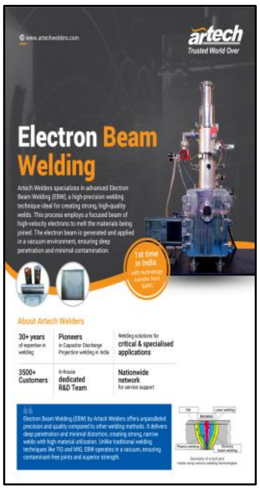
Technology transfer is the process by which knowledge, intellectual property and capabilities developed at its centres/units and elsewhere, utilising DAE's resources are licensed to external entities including industries in the public and private sector, State and Central Government organisations for commercialising the same during the licensing period. It is our mandate to actively pursue technology transfer so that benefits of the DAE programme are transferred to Indian industries, in both public and private sector. Technology Transfer & Collaboration Division is the nodal agency in DAE through which state-of-the-art/import substitute technologies developed by Department of Atomic Energy (DAE) is made available to the end-users on non-exclusive basis with complete hand holding support for commercialization. It interacts with all the Units of DAE, Government Institutions, Industries, and Educational Institutions for collaboration and technology commercialization. It offers an opportunity for employment generation and source of income for needy people. There about 220 different technologies available for transfer and are listed in the entrepreneur corner of BARC website. https://barc.gov.in/technologies/technology.html.

About **60** Agreements signed for Transferring **43** Technologies to **53** companies in 2024. The technologies are transferred after assessing the prospective transferees' current capabilities and interest in the commercialization. Apart from that, nine technology licenses were renewed in 2024.

Nine new technologies have been assessed and released in public domain for advertisement in the previous two years. The repository of technologies available for transfer is continuously updated and obsolete technologies are removed or upgraded. The scope and application of the technologies available for transfer is uploaded to the website with photographs and procedure for transfer of the technologies. Communication to industry and entrepreneurs about the benefits of the technologies available for transfer is essential for successful commercialization. TT&CD is participating in such events to inform the industry as well as the end-users regarding the products and the technologies developed by DAE. The licensees were contacted for the commercialization status and active licensees list is displayed on BARC website with their contact details. Commercialisation of technologies include production of boron carbide, soil organic carbon kit, electron beam welding equipment, hydrogel, chemical storage cabinets, hybrid granular sequencing reactor for sewage treatment, domestic and industrial water filters etc

300 KLD hgSBR STPs plant at Shirdi

750 lph Ultra Filtration based water purification unit at Central Railways platform, CSMT, Mumbai



Electron beam welding machine.

2. Consultancy services, collaboration and patent

BARC offers a wide range of services and consultancy to different DAE units and also to outside companies. TT&CD evaluates the costing of such services and consultancy offered by BARC. Usually agencies/ institutes in need of the service/ consultancy applies directly to TT&CD or to the concerned division offering the service/ consultancy who in turn would contact TT&CD for the costing of the same. TT&CD performs the calculation for costing of the services/ consultancy and the proposal is forwarded to TTSC for approval. Based on the approved costing, BARC raises the bill to the companies and institutes for payment. Five different consultancy services provided by various divisions of BARC within DAE units & outside companies in 2024.

Memorandum of Understanding is another mechanism through which collaboration work is carried out by BARC along with national institutes and other government/non-government agencies. MoU committee has been constituted) for scrutinizing all such agreements between BARC and academia/industry. Head, TT&CD is the member secretary of the committee. TT&CD through this MoU committee looks after the execution of new MoUs, their extension, and finally closure of the MoUs after their completion.

As Innovations needs to be protected for ensuring its intellectual property rights, TT&CD coordinates the meetings for evaluation of the merit of the Patent proposals forwarded to DAE. The inventor division submits a patent proposal to TT&CD in a prescribed format with adequate evidences supporting the invention and thorough patent search for discarding its obviousness and establishing its novelty. TT&CD constitutes a patent sub-committee of experts in the field of the proposal with Head, TT&CD as the convenor of the committee. The proposal is then cleared by Technology transfer subcommittee TTSC and sent to DAE IPR cell for further processing. Suitability of its filing and the countries in which the know-how is to be protected is decided at DAE IPR Cell. **Nine** patent proposals have been processed and forwarded to DAE IPR cell for further dealing out in 2024.TT&CD also plays a crucial role in ensuring returns from patent has been filed by inventors. It is also ensured that non-working patents are not renewed.

3. Atal Incubation Centres (AIC)

Established under the aegis of ATAL Innovation Mission, ATAL Incubation Centre AIC-BARC was setup in October 2020 as one of the four Aatma Nirbhar Bharat projects of DAE. AIC-BARC, aims to promote start-ups and other emerging entrepreneurs, thereby also opening up newer employment avenues. It will also tie up with MSME’s for scaling up and customizing BARC technologies to industrial standards.

As per ATAL Innovation Mission (AIM) guidelines, AIC BARC ANUSHAKTI FOUNDATION has been now set up and incorporated as a section 8 company under the Ministry of Corporate Affairs on 29 March 2025 and will be known in commercial parlance as AIC-ANUSHAKTI. The AIC ANUSHAKTI is supported by Bhabha Atomic Research Centre and owned by Department of Atomic Energy limited by shares of Rs. One lakh. The company will be managed by the Board of Directors appointed by Director BARC.

The mission behind the establishment of AIC ANUSHAKTI is to nurture a vibrant and sustainable technology translation ecosystem for advanced and globally competitive and allied technologies. The vision of AIC ANUSHAKTI is to develop AIC ANUSHAKTI to be one among the top state-of-art incubation centre in the country in the domain of deep technology, facilitating creativity, innovation, and entrepreneurship. AIC-ANUSHAKTI is BARC's arm for technology translation by which existing technologies at BARC are incubated for development in collaboration with industrial partners.

Till date, AIC ANUSHAKTI has executed 15 agreements for incubation with different startups and MSME's. Eight incubation programs launched till date are on BARC in-house spin off technologies which include M/s. Panacea Medical Technologies Pvt. Ltd, Karnataka for X band LINAC technology, M/s. AnandSparX Technology LLP, Surat for Water Treatment Plant using EB Accelerator technology, M/s Pratishna Engineers, Mumbai for Alkaline Water Electrolyzer technology, M/s Ace-Ex Industries, Mumbai for Handheld Gamma Spectrometer based on Cesium Iodide (CsI) Single Crystal technology, M/s Gir Gau Jatan Sansthan, Rajkot for Nisarguna Biogas Technology, M/s ONGC Energy Centre, Delhi for Process system for clean-up of dissolved oil and salt contaminated waste water for gainful utilization technology, M/s Vasantdada Sugar Institute, Pune for Chitosan Based Formulation For Sustainable Crop Production technology, M/s Hyurja Pvt. Ltd, Mumbai for Plasma pyrolysis of methane for zero-emission hydrogen production technology. M/s. Ace-Ex Industries have graduated in a year after completing the first prototype. M/s AnandSparX Technology has also graduated after completing the design for engineering scale up and is awaiting orders for establishing a commercial plant.

At present four more technologies are progressing in the collaborative incubation mode. Four incubatees signed agreement with AIC ANUSHAKTI for Collaborative incubation wherein BARC scientists and engineers will mentor the industry for co-development of various technologies. These include M/s Dipesh Engineering Works, Mumbai for Iodine Sulphur Thermo-chemical Process Plant for Hydrogen Production by splitting Water technology, Raipur Institute of Technology, Raipur for Optimization of Biogas and Biofertilizer production using Jatropha seed De-oiled cake (DOC) of Biodiesel plant technology, M/s Pluviago, Kerala for Bioavailable Cold Water Dissolvable Formulation of Astaxanthin and Pomegranate Peel Extract technology, M/s Ambetronics India Pvt. Ltd. for the Design, Development, Testing & Fabrication of Sensor Electrodes for Frying Oil Quality Tester & Dew Point Transmitter technology.

Startup entrepreneurship incubation for budding entrepreneurs is also in progress by M/s Wastech Pvt. Ltd, Mumbai and M/s Cassion, Mumbai for three different BARC technologies with low investment capital. These incubatees were selected through startup entrepreneurship workshops and pitching cohort sessions. Three Start-up Entrepreneurship workshops were organized at DAE Convention Centre, Anushaktinagar, Mumbai. Topics for the workshop were Dry and Wet waste management technologies, Clean Water Technologies and Food Processing Technologies. Technologies suitable for start-ups with investment up to 10 lakhs, their demonstration and business models were presented during workshop. Students pursuing final year and those who completed undergraduate studies in Sciences/Engineering/Commerce were invited for the event.

With the establishment of Section 8 company, AIC ANUSHAKTI will soon hire its management team comprising of CEO and incubation managers to look after the day-to-day activities. The scope of work will soon be enhanced to include technology transfer, incubation, translation, consultancy and service activities as well as training services. At present the incubation centre is operated from it's office at DAE convention Centre which will be later shifted to a full-fledged incubation center at Project House Anushaktinagar near AERB

4. Advanced Knowledge and RUrban Technology Implementation initiative (AKRUTI)

DAE has launched Societal Initiative for utilisation of Non-Power Applications (NPAs) and Spin-off technologies in all the areas in the field of Science & Technology for improvement of urban and rural sector for promotion of Entrepreneurship. Under Vision 10 for social outreach and awareness, strengthening of AKRUTI Programme, which primarily provides access to BARC developed technologies to all sections at affordable cost for deployment in rural sector. Ten AKRUTI Kendras have been established across the country for deployment of BARC technologies in rural and urban areas which include Shri Vitthal Education and Research Institute (SVERI) Pandharpur, Maharashtra, Brahmdevdada Mane Institute OF Technology (BMIT) Solapur, Maharashtra, Raipur Institute of Technology (RITEE) Raipur, Chattisgarh, Pt. Ravishankar Shukla University (PRSU) Raipur, Chattisgarh, Uttar Banga Krishi Vishwavidyalaya (UBKV), Cooch Behar, West Bengal, Dr. D. Y. Patil Arts, Commerce and Science College Pune, Maharashtra, Mahatma Gandhi University (MGU), Kottayam, Kerala, Punyashlok Ahilyadevi Holkar Solapur University Solapur, Maharashtra, Jai Hind College Mumbai and GITAM university Vishakhapatnam.

DAE has been putting constant endeavours for expanding AKRUTI programme at its various units all over India. NPCIL under its Corporate Social Responsibility (CSR) has set up AKRUTI Centres for demonstration of DAE developed technologies in the vicinity of Nuclear Power Plant sites. Under new sustainability plan, eight licenses for eight technologies were disbursed through AKRUTI Kendra - Tarapur, training for the same started at Kendra and revenue generation has also started for the Kendra.

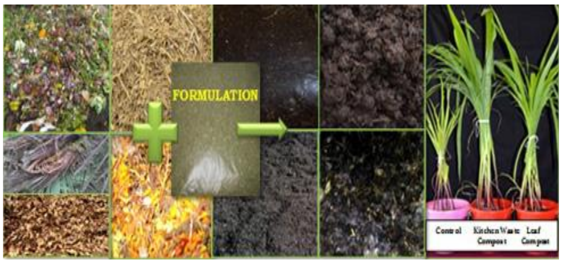
AKRUTI Kendra- UBKV Agreement was signed between BARC and Uttar Banga Krishi Vishwavidyalaya, Cooch Behar

AKRUTI Kendra- MGU Agreement was signed between BARC and Mahatma Gandhi University, Kottayam.

Apart from the above major undertakings, DAE technology awareness & transfer meets, lectures on Technology transfer mechanism in DAE, outreach programmes and technology exhibitions have been organized by TT&CD throughout the year. 'The Technology Powerhouse Book series of five booklets has been printed and booklet copies were distributed to various divisions and other DAE units. The same is available at DAE digital library. https://digilib.dae.gov.in/books/94603

5. Popular technologies developed by BARC

5.1. A Rapid Composting Technology for decomposition of dry leaves, kitchen waste and temple waste.



A single microbe (cellulolytic fungus) based formulation has been developed for Rapid decomposition of many types of biodegradable wastes like kitchen/market waste, dry plant matter (including coconut leaves), straw/agricultural residue and holy waste from temples.

5.2. Foldable Solar Dryer

Suitable for drying up to 25 kg of fresh agricultural produce such as grapes, onion, mango pulp, green leafy vegetables etc. Dried product is hygienic compared to open floor drying, comparatively safe and secured from animals, insects and dust.

5.3. Soil Organic Carbon Detection Kit

Technology helps farmers to analyze the soil organic carbon on the field itself and take corrective decision without spending time.

5.4.Minimally Processed Ready-to-eat (RTE) Apple Slices

This technology describes a process for development of minimally processed RTE apple slices with an improved shelf life of 10-12 days at 10 ºC without chemicals.

5.5. Microfine Neem Biopesticide

Organic biopesticide to control insect pests under field condition.

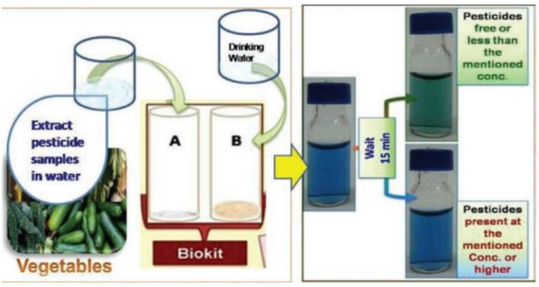
5.6. De-bittered Bitter Gourd (Karela) Juice with High Antidiabetic Activity

Present technology describes the procedure for preparation of non-bitter Karela juice having high bioactivity.

5.7. A post-harvest technology for development of Intermediate Moisture Shrimp

Fish & fishery products are highly perishable and hence they are consumed mainly in fresh or dried form. It can be preserved for six months with moisture content by this technology.

5.8. Biosensor Kit (Biokit) for Detection of Organophosphate (OP) and Organocarbamate (OC) Pesticides



Biokit is a visual colorimetric detection kit detecting the presence of pesticides in food commodities such as vegetables and fruits.

5.9. Development of Instant Fish Soup Powder

This technology developed by BARC for development of Instant fish soup powder which is high in nutrition and low in calories.

5.10. Shelf Stable Oil Free Potato Chips of Different Flavours

This technology describes a process for development of oil-free potato chips in six flavours with lower added sugar and starch content.

5.11. Nutritious Ready to Eat (RTE) fish spread.

This technology delineates the methodology for preparation of Ready-to-Eat (RTE) fish spread which is high in protein, low in fat food.

5.12. Fluoride Detection Kit for Groundwater (FDK)

FDK used for quick and easy estimation of fluoride concentration in ground water.

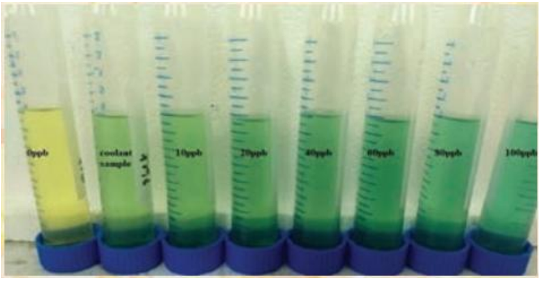
5.13. On-line Domestic water purifier based on Ultra Filtration Polysulfone membrane

On-line domestic water purifier used to purify the domestic water from microorganisms, colour, odour, suspended solids, organics and it removes bacteria to the extent of >99.99%(4 log scale). It does not need electricity or addition of any chemical and work between the hydrostatic head(5 psig to 35 psig), it can produce about 40 liters of pure water per day at about 10 psig head.

5.14. Multi Effect Distillation with Thermo Vapour Compression (MED-TVC) Desalination Technology.

MED-TVC technology may be used for production of distilled water from Seawater.

5.15. Process to Determine parts per billion levels of Ammonia in Water with Emphasis on Boiler Coolant Water

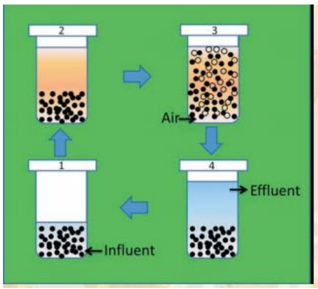


It is used for determination of NH3 at ppb levels in boiler coolant water in engineering and power industries.

5.16. NISARGRUNA Biogas plant for biodegradable waste management

The technology is used for the processing and disposal of different types of biodegradable wastes such as Municipal solid waste, kitchen waste, food industry waste, agriculture waste, abattoir waste etc. in lieu of production of Biogas and manure.

5.17. Hybrid granular sequencing batch reactor (hgSBR) for wastewater treatment



hgSBR is a compact biological wastewater treatment system for effective removal of contaminants from domestic and industrial waste waters.

5.18. Compact Helical Biodegradable Waste Converter SHESHA.

I may be used to manage the biodegradable waste generated in smaller housing societies, restaurants and produce fuel and manure for soil.

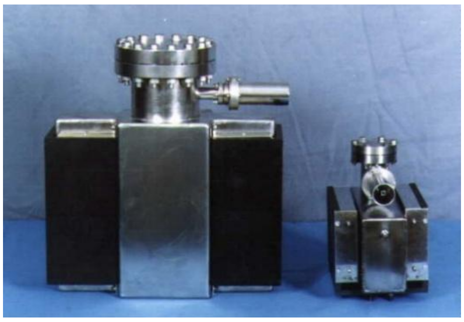
5.19. Smart Radon Monitor

Radon is a radioactive gas and its level in atmosphere and in different sources is required to be monitored. The Smart Radon Monitor (SRM) with programmable sampling and counting cycle time is able to measure radon concentrations from different sources in a continuous unattended fashion.

5.20. Mercury visual detection kit (MVDK) for groundwater

MVDK is used for onsite visual monitoring of safe and toxic levels of mercury (Hg) in water.

5.21. Triode Sputter Ion Pumps



Triode Sputter Ion Pumps operate in the pressure range 10 –3 to 10-10 Torr. These pumps are used to create UHV in charged particle accelerators, surface analytical spectrometers, mass spectrometers etc. Technology for 35, 70, 140 & 270 LPS capacity are available.

5.22. Radiation assisted Adsorbent technology for Textile Effluent Decolouration (RAd-TED)

A radiation grafted adsorbent-based treatment technology (Rad-TED) which is comparatively simple, efficient and highly effective in decolorizing coloured waste water from cotton textile industries.

About the Author:

Daniel Babu P is an applied electronics and instrumentation engineer from College of Engineering Trivandrum, Kerala. He also holds a post graduate diploma in software technology from NCST. He passed out from 34th batch of BARC training school and has vast experience in process instrumentation and control of nuclear recycle projects in spent fuel reprocessing and waste management. He has also experience in Project LHC at CERN Geneva during 2003-04 and played a crucial role in testing of superconducting magnets. He is also an expert in software IV&V for C&I systems for nuclear facilities and has authored many guides for computer security for Indian nuclear facilities. At present he is Heading Technology Transfer & Collaboration division, TT&CD, BARC looking after technology transfer activities, ATAL incubation centre, management of activities related to MoU, AKRUTI and patent screening. He holds additional charge as Head of Public Awareness and Media Interaction Division at DAE.