

Souvenir



A Special Issue of ASSET Bulletin on the Occasion of

DAE-BRNS Theme Meeting on RADIATION PROCESSING OF SEWAGE SLUDGE (RPSS-2024)

June 15, 2024

Multi Purpose Hall, T.S.H.

Anushaktinagar, Mumbai-85, India

Organized

By

Radiochemistry & Isotope Group, BARC, DAE

Trombay, Mumbai - 400085

In Association With

Association of Separation Scientists and Technologists
(ASSET)

RPSS-2024

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Editors:

A. Bhattacharyya, Arijit Ghoshal, K. A. Dubey

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भारत सरकार
Government of India

विवेक भसीन
Vivek Bhasin

निदेशक, भाभा परमाणु अनुसंधान केंद्र
Director, Bhabha Atomic Research Centre
सदस्य, परमाणु ऊर्जा आयोग
Member, Atomic Energy Commission



MESSAGE

I am delighted to know that the One-Day DAE-BRNS Theme Meeting on "Radiation Processing of Sewage Sludge (RPSS-2024)" is being organized by the Radiochemistry & Isotope Group, BARC, in association with the Association of Separation Scientists and Technologists (ASSET) on June 15, 2024, at the Multipurpose Hall, TSH Anushakti Nagar, Mumbai.

For the past several decades, the Bhabha Atomic Research Centre (BARC) has been actively engaged in the advancement of societal applications of radiation technology. In Vadodara, DAE's Sludge Hygienisation Research Irradiator (SHRI) has been operational, effectively treating liquid sludge through irradiation. Moreover, in a significant stride, DAE has collaborated with the municipal corporations of Ahmedabad and Indore to establish cutting-edge dry sewage sludge hygienisation plants, aiming to streamline and economize the treatment process.

The technical program of RPSS-2024 is meticulously structured to cover radiation technology for sewage sludge management, addressing the challenges and exploring potential solutions for sewage management in India, examining the utilization of radiation-treated sewage sludge as manure, exploring the potential of radiation-treated sewage sludge as a versatile energy source, investigating the application of biochar derived from sewage sludge in separation science, conducting techno-economic analyses of sludge hygienisation irradiators, studying heavy metal contamination in sewage sludge and various remediation approaches, and exploring the role of radiation technology in enhancing soil health.

I am sure that RPSS-2024 will provide a good platform for enhancing interdisciplinary collaborations among R&D Scientists, Industrialists, and Academicians. I am pleased to know that more than 150 delegates (including experts, guests, and invitees) from DAE and non-DAE institutes will participate in RPSS-2024. I am also happy that after one day of scientific deliberations, a panel discussion has been scheduled on the topic "Radiation Processing of Sewage Sludge."

I congratulate all organizers of RPSS-2024 and convey my good wishes to them for organizing Theme Meeting on topic which has direct relevance to BARC as well as DAE Programs.

I wish the Theme Meeting RPSS-2024 a grand success.


(Vivek Bhasin)

13.06.2024



From President's desk



Dear ASSET members,

The Department of Atomic Energy (DAE) has been at the forefront of developing and promoting societal applications of radiation technology for the past three decades. The Sludge Hygienisation Research Irradiator (SHRI) in Vadodara, operated by DAE, has been effectively treating liquid sludge through irradiation. The establishment of state-of-the-art dry sewage sludge hygienisation plants in collaboration with the municipal corporations of Ahmadabad and Indore marks a significant advancement in optimizing the process. ASSET is co-organizing a One-Day DAE-BRNS Theme Meeting on 'Radiation Processing of Sewage Sludge (RPSS-2024)' on June 15, 2024, at the Multipurpose Hall, TSH. RPSS-2024 will provide a valuable platform for academicians, technologists, researchers, and representatives from various stakeholders, including municipal corporations and policymakers, to engage in discussions and exchange ideas on various aspects of sewage sludge management. The diverse range of topics, to be covered during the Theme Meeting promises to provide valuable insights and solutions for researchers and practitioners in the field.

I wholeheartedly join you in wishing the Theme Meeting RPSS-2024 a resounding success. May it foster fruitful discussions, meaningful collaborations, and significant advancements in the field of radiation processing of sewage sludge, contributing to the development of sustainable solutions for the benefit of our society. ASSET, as always, will be in the forefront for facilitating such technologies for societal benefits.

The help rendered by Dr. K.A. Dubey and Dr. Y.K. Bhardwaj in this regard is highly appreciated. I thank all the contributors to the Bulletin and ASSET members for their efforts in organizing this important event.

A handwritten signature in black ink, appearing to read 'P.K. Mohapatra'.

P.K. Mohapatra

Editor's Note

Dear ASSET Members,

As you all know ASSET has a mandate of publishing scientific bulletins on various topics under separation science and technology. Separation science has a significant role for the societal benefit in nuclear, pharmaceuticals, chemicals and other industries. In this regard we have already published issues covering the topics like, uranium harvesting for nuclear industries, radiopharmaceuticals applications.

Recently we also publishes a thematic bulletin on Waste water Remediation Strategies as water has not alternate for the survival of the human civilization.

With the growing populations, the management of the sewage sludge is a major concern to the human society. We know that the radiation is being applied in various fields for the societal benefit like water purification, food prcessing, sterilization of medical and other products etc. Hygenization of the sewage sludge is nowadays addressed by using this radiation based technology. In this thematic issue we are, therefore, covering this important topic "Radiation Processing of Sewage Sludge: Opportunities, Experiences and Impediments" which is being released during the ASSET one day theme meeting on the same topic.

I would like to thank all the distinguished authors for their contribution in bringing out this thematic bulletin.

I want to specially thank Dr. K.A. Dubey and Mr. Arijit Ghoshal of RTDD for collecting the articles and their support for bringing out this thematic bulletin.

I am thankful to Dr. P.K. Mohapatra, President ASSET and Dr. S. Jeyakumar and Dr. S.C. Tripathi, Vice-Presidents, ASSET for their support in bringing out this bulletin.

Finally, thank you all for your cooperation.

A. Bhattacharyya

Editor, ASSET

Radiochemistry Division,

BARC, Trombay, Mumbai-400085

DAE-BRNS Theme meeting on
Radiation Processing of Sewage Sludge (RPSS-2024)
June 15th 2024, Multipurpose Hall, TSH, Anushaktinagar, Mumbai-400085

09.00-09.30		Registration
09.30-10.00		Inaugural Session Welcome Address: Dr. K. A. Dubey, Convener, RPSS Opening Address: Dr. P. K. Mohapatra, Chairman, RPSS Address: Dr. Y. K. Bharadwaj, Co-Chairman, RPSS Address: Dr. D. K. Aswal, Chief Guest Address: Prof. T. K. Behera, Guest of Honour Vote of Thanks: Shri N. K. Garg, Secretary, RPSS
10.00-10.30	Keynote Address	Prof. S. Pillai Director, National Center for Electron Beam Research, Texas A&M, USA <i>Electron Beam Processing for Societal Applications: Challenges and Opportunities</i>
10.30-11.00		High Tea
Technical Session I (11:00-13:00)		
11.00-11.30	IT1	Prof. Tusar Kanti Behera Director, ICAR-Indian Institute of Vegetable Research, Varanasi, UP <i>Advancements in Organic Fertilizers for Vegetable Cultivation</i>
11.30-12.00	IT2	Prof. Srikanth Mutnuri Professor & Dean, Applied and Environmental Biotechnology Laboratory, Dept. of Biological Sciences, BITS Pilani, Goa <i>Bioremediation of Black/Gray water</i>
12.00-12.30	IT3	Dr. Dattatreya M. Kadam Principal Scientist and Head, Engineering Technology Transfer Division, ICAR-CIRCOT, Mumbai <i>Applications of Organic Fertilizers in the Cotton Industry</i>
12.30-13.00	IT4	Dr. Archana Kale Head R&D, Rashtriya Chemicals and Fertilizers Limited (RCF) <i>Development and Application of Sludge-Based Organic Fertilizers in RCF</i>
13:00-14:00		Lunch
Technical Session II (14:00-16:00)		
14.00-14.30	IT5	Dr. Shraddha Singh Scientific Officer, NABTD, BARC <i>Strategies for Heavy Metal Remediation from Soil and Sludge</i>
14.30-15.00	IT6	Shri. Amit Srivastava Deputy General Manager, BRIT <i>Radiation Processing for Hygienisation and Sterilization: Current Trends</i>
15.00-15.30	IT7	Shri. Naresh Kumar Scientific Officer, RTDD, BARC <i>SHRI: Advanced Radiation Processing of Liquid Sludge</i>
15.30-16.00		Panel Discussion
Concluding Remarks by Dr. P. K. Mohapatra (Chairman, RPSS-2024)		
Tea		

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Note: The contents are intended for Teaching and Training Purpose only

Basics of High Energy Radiation and its effects

Dr. N. K. Goel

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Radiation: Radiation is energy travelling through space which is constituents of small packets of energy called photons. Energy of photon is defined in terms of frequency (ν) or wavelength (λ) of radiation as

$$E = h \cdot \nu = h \cdot c / \lambda \quad (1)$$

Where:

h is Planck's constant $= 6.62607004 \times 10^{-34} \text{ m}^2 \text{ kg/s}$

c is velocity of light $= 3 \times 10^8 \text{ m/s}$

Classification of the radiations: Radiations can be classified broadly into two classes depending on its nature:

- 1) **Electromagnetic Radiation** (Wave Nature e. g. Radio waves, Infrared Rays, Ultraviolet Rays, Visible rays and Gamma rays etc.)
- 2) **Particulate Radiation** (Alpha radiation (α), Beta radiation (β), and Neutron (n) etc.)

Electromagnetic Spectrum: All radiations are specific to their wavelength or frequency and hence the energy as given by the equation (1). The radiations are further arranged as per their energy which is named as Electromagnetic spectrum (Figure 1). Radio frequency which is placed to extreme left of the spectrum is lowest in their energy and Gamma Radiation to extreme right with highest of the energy.

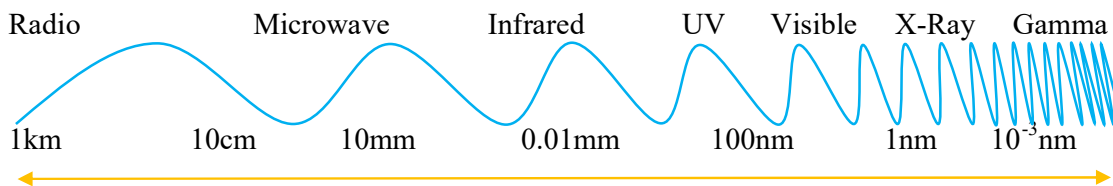


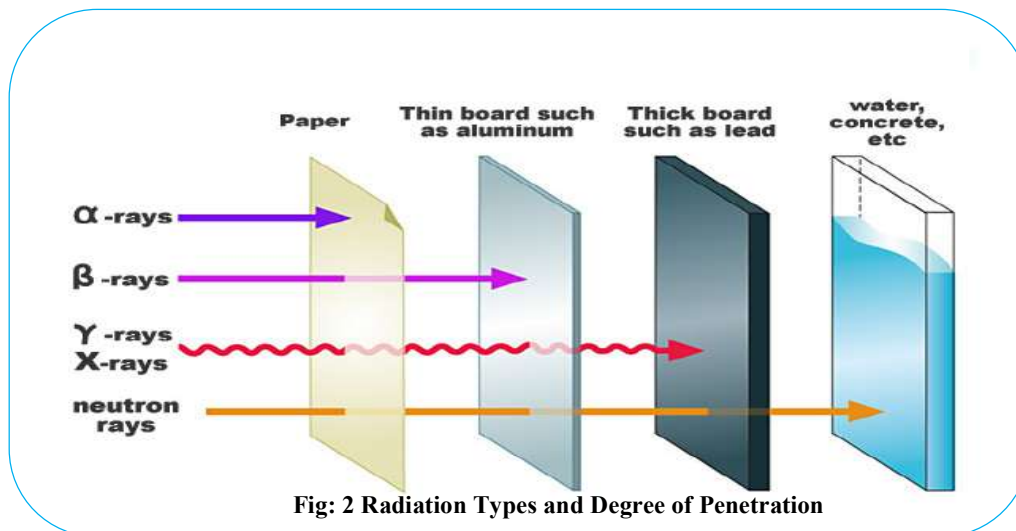
Fig. 1 Electromagnetic Spectrum

Mainly all radiations from radio waves to X-rays have been already investigated thoroughly and explored their applications in various sphere of life of human beings. Radio wave has well established applications of communications like TV/Radio via its transmission from one point to another at distant (in range of Km). Microwaves are used in radar, in communications, and for heating in microwave ovens and in various industrial processes. There are numerous applications of Infrared radiation emitted in form of heat e.g.

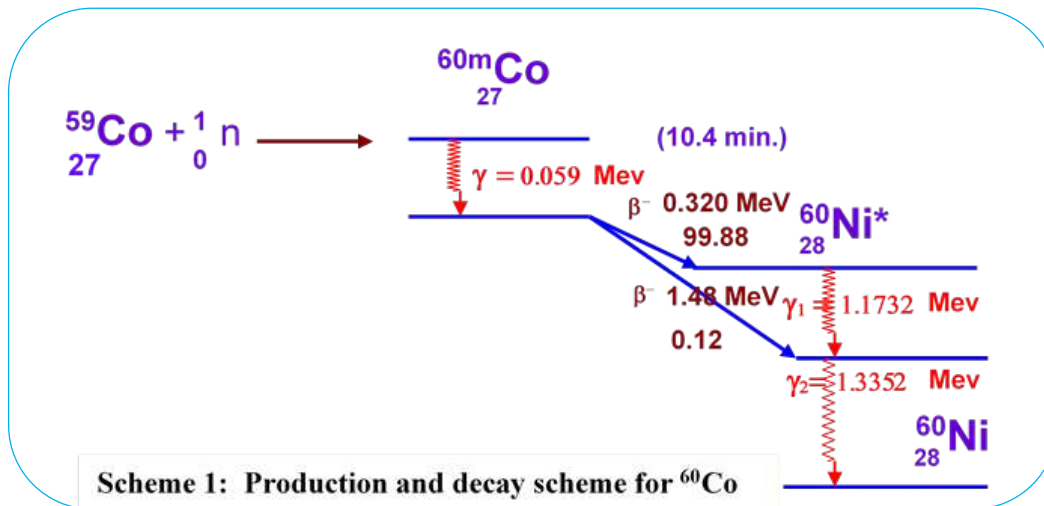
heating, night vision, climatology, astronomy and many more. Visible, UV and X-ray have well known many established applications like photosynthesis, electricals & electronic industry, medical & Industrial respectively.

Radioisotopes: Radioisotopes are radionuclide with unstable combination of neutrons and protons in the nucleus defined in term of n/p ratio. If the ratio lies out of, 1-1.6 range called stability zone, isotope is called radioisotope with unstable nuclei. These nuclei possess excessive energy due to the instability and emitted in form of electromagnetic radiation like gamma radiation or/and new particles (alpha particle or beta particle). This emission is termed as radioactive decay. These radioisotopes are characterised by their unique properties like half-life ($t_{1/2}$), decay constant (λ) and energy of emitted radiation. These radioisotopes occur in nature as well as may be produced artificially by bombardment of high energy particles like alpha, neutron, proton on stable nuclei called transmutation. For example, Tritium (^3H), ^{17}O , ^{40}K are found in nature while ^{60}Co , ^{18}F , ^{82}Br , ^{192}Ir are produced in nuclear reactors. There are numerous applications of both natural as well as artificial radioisotopes in Industry, Healthcare and Environment.

High energy radiations: High energy radiations are named because of their properties of ionising the matter through which they pass. These radiations have sufficient energy to ionise the matter. High energy radiations are emitted from the unstable nuclei e.g. Gamma radiation, alpha radiation, beta radiation, neutron radiation etc. These radiations are mainly classified in two types namely; wave nature (gamma radiation) and particulate radiation (alpha, beta, neutron etc.). In this article gamma radiations and electron beam, their properties, interaction with matter and applications will be emphasised. One of the important properties, penetration through the medium, is given in the figure 2. Heavy charged particles like alpha rays have the very low range of penetration but deposit energy in a very small region while gamma being electromagnetic in nature, has the range in hundreds of meters in air. High penetrating power of gamma is basis of many developed radiation technologies like sterilization of medical products in the packed form.



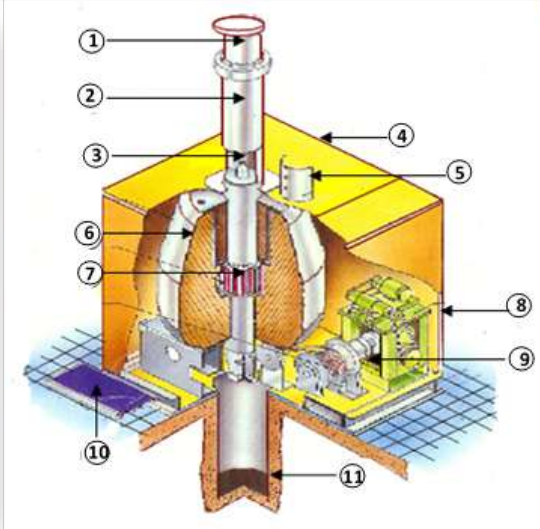
Gamma Radiation: Gamma rays are the most energetic form of electromagnetic radiation, with a very short wavelength of less than one-tenth of a nanometre with very high penetration. This radiation commonly has energy range of a few hundred KeV to ~10 MeV. The gamma ray has no mass and no charge. Gamma rays interact with material by colliding with the electrons in the shells of atoms. They lose their energy slowly in material, being able to travel significant distances before stopping. Depending on their initial energy, gamma rays can travel from 1 to hundreds of meters in air and can easily go right through people. ^{60}Co radioisotope is produced by irradiating natural cobalt (^{59}Co) in the form of pellets, small slugs or thin disks in nuclear reactor by $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ reaction to give a uniformly active material which emits two γ rays of energies 1.33 and 1.17 MeV as shown below in the decay scheme 1.



Gamma Radiation Machine: Gamma irradiation of the samples was carried at room temperature using Gamma Chamber 5000, supplied by the Board of Radiation & Isotope Technology (BRIT), Mumbai, INDIA. Figure 3 shows the schematic of gamma chamber used for studies. Gamma chambers mainly consist of a set of stationary Cobalt-60 (^{60}Co) sources placed in a cylindrical cage surrounded by a lead shield provided around the source to keep external radiation field well within the permissible limits. The sample for irradiation is placed in an irradiation chamber located in the vertical drawer inside the lead flask. The drawer can be moved up and down with the help of a system of motorized drive which enables precise positioning of the irradiation chamber at the centre of the radiation field.

Electron Beam: Electron beam is stream of high energy electrons generally with 500keV to 10 MeV. These high energy electrons are obtained by using particle accelerator namely linear accelerator (Linac) or cyclotron, where low energy electrons are accelerated through variable potential gradient up to target energy, generally in range of MeV. Basics of high energy electrons are like cathode rays used in cathode ray tube (CRT) based televisions where electrons are accelerated to low energy from 1-20KeV and guided to fluorescent screen for imaging. High energy based Linac and CRT are shown in the figure 4. These high energy

electrons are being utilised for various radiation-based technologies like medical sterilization, tyre industry, colour gem industry etc. Most of the radiation technologies are based on either electron beam or gamma radiation.



1. Stirrer Motor 2. Central Drawer 3. Sample holder 4. External Cabinet 5. Removable Cover 6. Lead Flask 7. Source Cage 8. Mechanical Driving system 9. Wire rope 10. Platform 11. Concrete Pit

Fig: 3 Gamma Chamber 5000 and sectional view

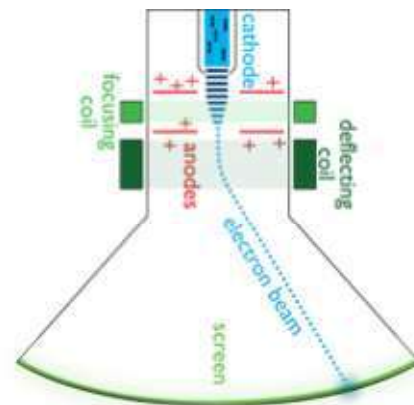
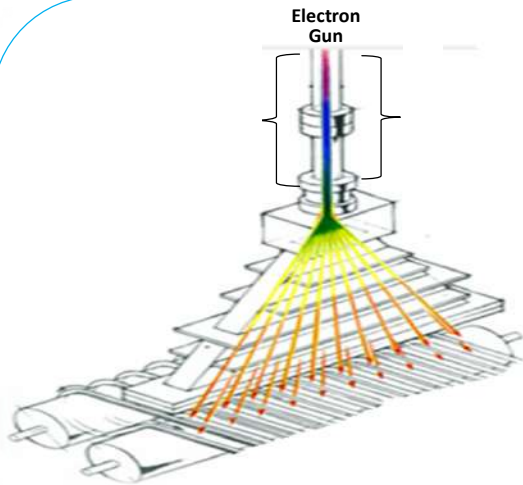


Fig: 4 High energy electron beams from Linac and low energy from CRT

Interaction of Radiation with matter

1) Electromagnetic Radiation (Gamma Radiation): Electromagnetic radiations of wavelength less than $100 \text{ \AA}$ belong to the class of ionizing radiation. They are usually called X-rays (extra nuclear origin) or γ rays (produced from the atomic nuclei). The gamma rays emitted by radioactive isotopes are mono-energetic, possessing one or more discrete energies, for example ^{60}Co emits γ -photons of energy 1.332MeV and 1.173MeV . For a narrow beam, the intensity of gamma radiation transmitted through an absorber is given by:

$$I = I_0 e^{-\mu x} \quad (2)$$

Where, I_0 is the incident radiation intensity, x is the thickness of material through which radiation has traversed and μ is the linear attenuation coefficient, which is the sum of a number of partial coefficients representing different processes occurring inside the absorber. These are (i) Photoelectric effect, (ii) Compton scattering, (iii) Pair production (iv) coherent scattering and (v) photonuclear reactions. The relative importance of each process depends on the photon energy and the atomic number of the absorbing material. Coherent scattering is of importance for low energy photons ($<0.1\text{MeV}$), photonuclear reactions are possible with photons of energies in the range of 2 to 8MeV for low Z materials and in the region of 7- 20MeV for high Z materials. Thus, for gamma radiation emitted by ^{60}Co source, only the first three interaction processes are of importance

2) Particulate Radiation

(a) Electrons: Electron interacts with matter via four processes namely, emission of Bremsstrahlung radiation, inelastic collision, elastic collision and Cerenkov emission. The relative importance of these processes depends mostly on the energy of the electrons and to a lesser extent on the nature of the absorbing material.

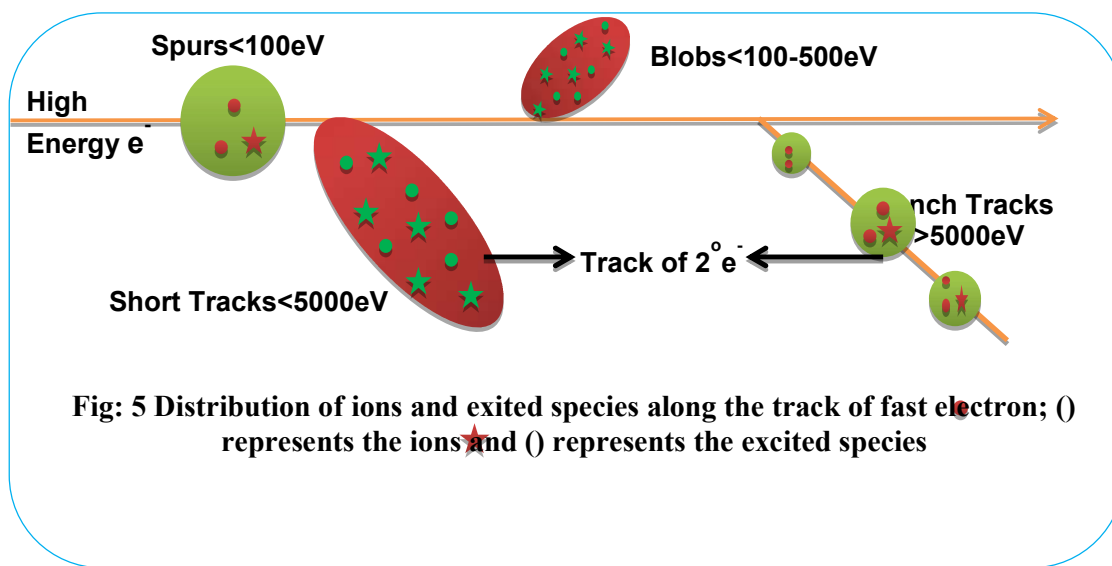
(b) Heavy charged particles

The interaction of heavy charged particles with matter is the same as that of electrons, i.e., Bremsstrahlung emission, inelastic collision and elastic scattering. The most important among these processes by which charged particle interact with matter is inelastic collision. As heavy charged particles have higher mass than electrons, for a given energy, they have a much higher linear energy transfer (LET), which give rise to high local concentration of primary species and leads to recombination in spurs to yield molecular products.

Distribution of active species in the system – Track Structure

The electrons from Compton scattering of ^{60}Co γ -rays have an average energy of 440keV . These electrons, also termed as δ -rays, bring about further ionization and excitation. Such events along the main track or the δ -ray branch track are called isolated spurs. In water, the isolated spurs contain on an average ~ 6 active species and $\sim 100\text{eV}$ energy is involved. When δ -ray electron energy is $< 5\text{keV}$, its penetration becomes very less and the spurs so

formed in close vicinity overlap and take cylindrical shape, known as short tracks. As the electron energy becomes less than 500eV, even denser regions of ionization, which look like large spurs, called as blobs, are produced (figure5). The typical energy distribution ratio for a 440keV electron in water is spur (64%), short tracks (25%) and blobs (11%). In contrast to this, for heavy charged particles (high LET), more energy will be deposited in blobs and short tracks than in isolated spurs.



Radiation chemistry of water: Understanding of radiation chemistry of water is of importance as water is present in most biological and chemical systems. For water, the sequence of events like formation and solvation of the primary species, and the time scale of events initiated either by fast electrons from an accelerator or by ^{60}Co gamma-rays is illustrated in figure6. High energy radiation is deposited in energy in 10^{-16} seconds in the substrate forming positively charged ions, electrons and excited species. Energetically unstable positively charged ions (H_2O^+) undergo ion-molecule reaction in 10^{-14} seconds producing $\text{OH}^\bullet$ radicals. The excited water molecules decompose in 10^{-14} seconds yielding $\text{H}^\bullet$ and $\text{OH}^\bullet$ radicals. The electron released during ionization can also bring about further ionization provided it has sufficient kinetic energy. Eventually, its energy will fall below the ionization threshold of water and then it dissipates rest of its energy by exciting vibrational and rotational modes of the solvent molecules. Finally, it would be localized in a potential energy well long enough to become solvated as a result of molecular dipoles rotating under the influence of the negative charge, and thus get stabilized. The electrons get thermalized in about 10^{-13} seconds and subsequently get hydrated or solvated in less than 10^{-12} seconds and called hydrated electron (e_{aq}^-). These species viz. hydrated electrons, hydrogen atoms and hydroxyl radicals, formed in the spurs, can react with one another to reform water or molecular products, H_2 and H_2O_2 , while the remaining escape into the bulk solution. This

spur expansion is complete in about 10^{-7} s. The reactions occurring during spur expansion are listed in Table 1. After about 10^{-7} second, the species are distributed homogeneously in the bulk and are known as primary species. Main species produced are hydrated electrons e_{aq}^- , $OH^\bullet$, $H^\bullet$ and molecular products H_2 and H_2O_2 . These species can subsequently react with solutes present in the system. In water, 10^{-7} seconds is the lifetime of the radicals reacting at a diffusion-controlled rate with a solute whose concentration is $10^{-3} \text{ mol dm}^{-3}$. Under these conditions the G-values of e_{aq}^- , $H^\bullet$ and $OH^\bullet$ radicals at 10^{-7} second are shown in the figure: 6.

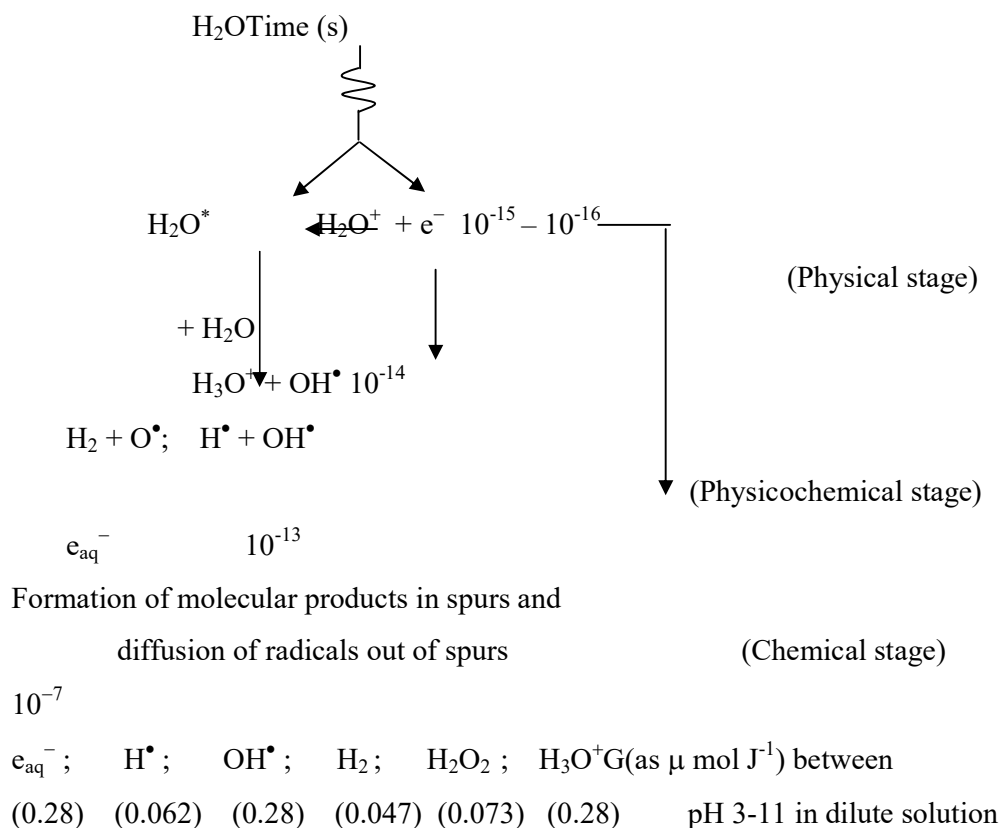


Fig: 6 Sequence of events in water Radiolysis and formation of primary species from 10^{-16} to 10^{-7} second

Table 1 Spur Reactions in Water

Reactions	$k \times 10^{-10} (\text{dm}^3 \text{mol}^{-1} \text{s}^{-1})$
$e_{\text{aq}}^- + e_{\text{aq}}^- \text{H}_2 \xrightarrow{+} 2\text{OH}^\bullet$	0.55
$e_{\text{aq}}^- + \text{OH}^\bullet \longrightarrow \text{OH}^-$	3.0
$e_{\text{aq}}^- + \text{H}_3\text{O}^+ \longrightarrow \text{H}^\bullet + \text{H}_2\text{O}$	2.3
$e_{\text{aq}}^- + \text{H}^\bullet \longrightarrow \text{H}_2 + \text{OH}^-$	2.5
$\text{H}^\bullet + \text{H}^\bullet \longrightarrow \text{H}_2$	1.3
$\text{OH}^\bullet + \text{OH}^\bullet \longrightarrow \text{H}_2\text{O}_2$	0.53
$\text{OH}^\bullet + \text{H}^\bullet \longrightarrow \text{H}_2\text{O}$	3.2
$\text{H}_3\text{O}^+ + \text{OH}^- \longrightarrow 2\text{H}_2\text{O}$	14.3

Effect of High Energy Radiation on Living cells: The cell is the basic structural, functional and biological unit of all known living organisms and it is the smallest unit of life that can replicate independently, and cells are often called the building blocks of life. The cell contains cytoplasm surrounded by cell membranes including various biomolecules like proteins, nucleic acid which performs different biological activities. Prolonged exposure of the living cell to high-energy radiation can ionize constituent atoms and molecules within cells, creating charged particles (ions) and free radicals. These ions and free radicals can cause damage to cellular components, including DNA, proteins, and cell membranes and hence has detrimental effects on living cell.

Deoxyribonucleic acid (DNA) is a most crucial molecule of the living cell that carries the genetic instructions used in the growth, development, functioning and reproduction of all known living organisms from smallest to largest. Therefore, interaction of high energy radiation with DNA is the most investigated area of research and damage to DNA is generally called genetic injury. There are two ways of interaction of radiation with DNA molecule a) Direct Effect and b) Indirect effect. **a) Direct Effect:** In direct effect, energy of high energy radiation is deposited by direct action to the interacting molecules (DNA) causes radiochemical damage. In radiochemical damage, radiation may disrupt in double/single strands or/and hydrogen bonding or/and base linkage of DNA damage to DNA. It may result in genetical change called mutation or damage to such an extent causing the non-functioning of DNA and hence death of the cell. Schematic of direct action have been depicted in figure 7. **b) Indirect Effect:** Most of the living cells are containing gel like fluid in the cell surrounded by the membrane. Main component of the fluid is water. Therefore, there is high probability of interaction of radiation with water. Highly energetic species like e_{aq}^- , $\text{OH}^\bullet$, $\text{H}^\bullet$ are produced after interaction of radiation with water called radiolysis as shown in figure 6. These highly energetic species then interact with DNA resulting in same effect as by direct action. This type of interaction is called indirect effect which is shown in the figure 7.

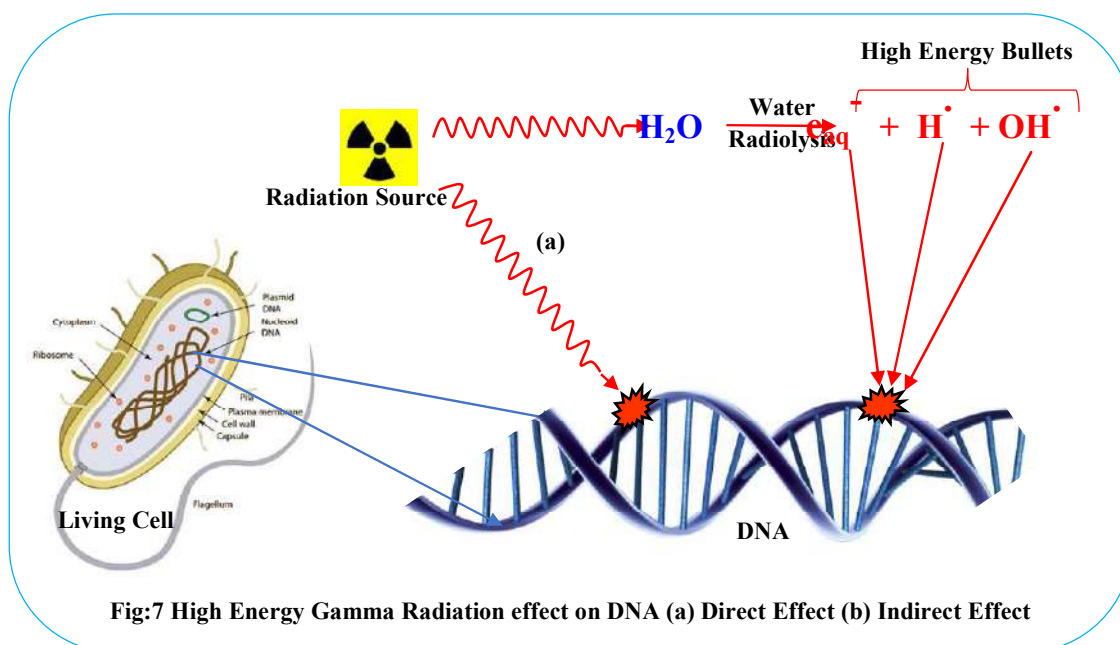


Fig:7 High Energy Gamma Radiation effect on DNA (a) Direct Effect (b) Indirect Effect

Overall, the effects of high-energy radiation on living cells are complex and can vary depending on factors such as the type of radiation, dose, duration of exposure, and the sensitivity of the cells or tissues involved. The interaction of radiation causes various radiochemical changes in the living and non-living material. These radiochemical changes in the interacting material may be guided for the various target applications in the areas of environment, industry and healthcare. Radiations effects generally can be used in two ways by destructing the living cells in controlled manner after exposure to calculated absorbed dose for the particular applications.

(a) Radiation Therapy in Medicine: In the field of medicine, ionizing radiations are used to target and destroy cancerous cells in a controlled manner which are fast growing living cells due to undergone genetic mutations or alterations, leading to uncontrolled growth and proliferation. This process, known as radiation therapy or radiotherapy, involves delivering carefully calculated doses of radiation to the tumour site while minimizing exposure to surrounding healthy tissues. Radiation therapy can be delivered externally using machines such as linear accelerators or internally via implanted radioactive sources (brachytherapy). By damaging the DNA of cancer cells, radiation therapy aims to halt their growth and induce cell death, ultimately shrinking or eliminating the tumour as shown in the figure 8.

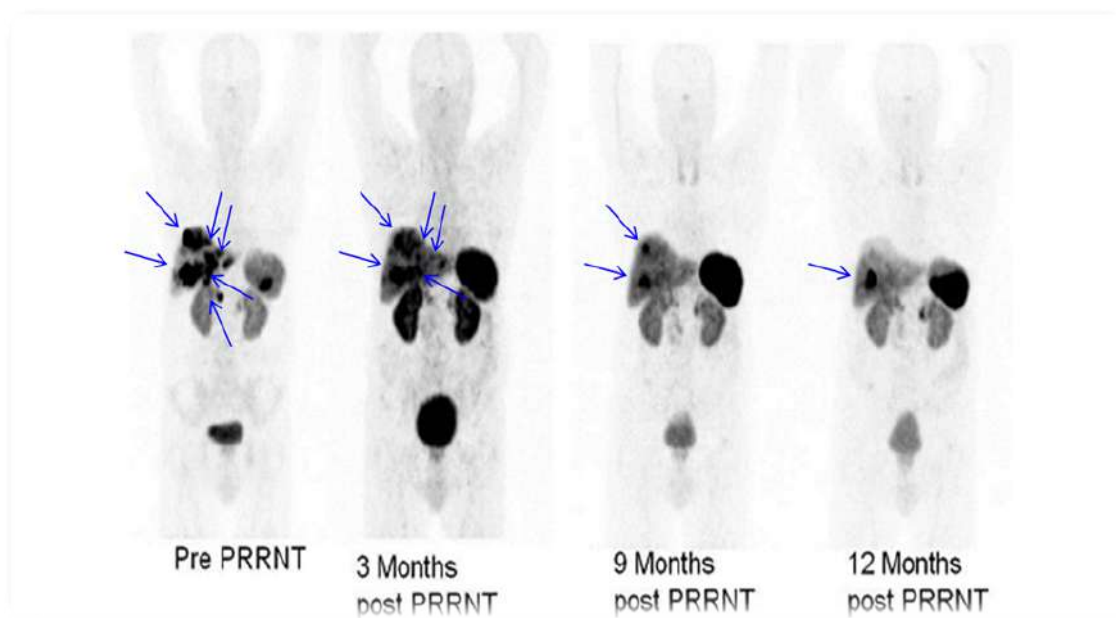


Figure 8: Peptide Receptor Radio-Nuclide Therapy (PRRNT)

b) Sterilization: Ionizing radiations also play vital role in sterilization and hygienisation purposes in various industries, including healthcare, pharmaceuticals and food processing. General principal involves in both sterilization and hygienisation is to bring down the microbial load to certain limit to avoid the spread of microbial infection. Exposure to ionizing radiation effectively kills or inactivates microorganisms such as bacteria, viruses, and fungi by damaging their DNA or other cellular components by direct or indirect method. This process is particularly useful for sterilizing medical equipment, pharmaceutical products with many inherent advantages by the sterilization process (Figure 9).



Figure 9: Medical product sterilization by radiation @25kGy absorbed dose

(c) Hygienisation: Waste management particularly generated from the household discharge in large amount on daily basis, need holistic approach to mitigate associated risks due to high microbial loads in the released sewage water to protect public health and the environment. Radiation Hygienisation offers advantages such as effectiveness, scalability, and the ability to

treat large volumes. Depending upon the sludge states like in the form of solid or slurry after primary treatment, exposure to high energy radiation for pre-calibrated absorbed doses can be adopted to lower down the microbial loads up to acceptable limits. The hygienisation process not only treat the generated waste from household to protect public health and environment but also convert waste to value added products in the form of manure which is a rich source of many macro and micro nutrients for the soil (Figure 10).

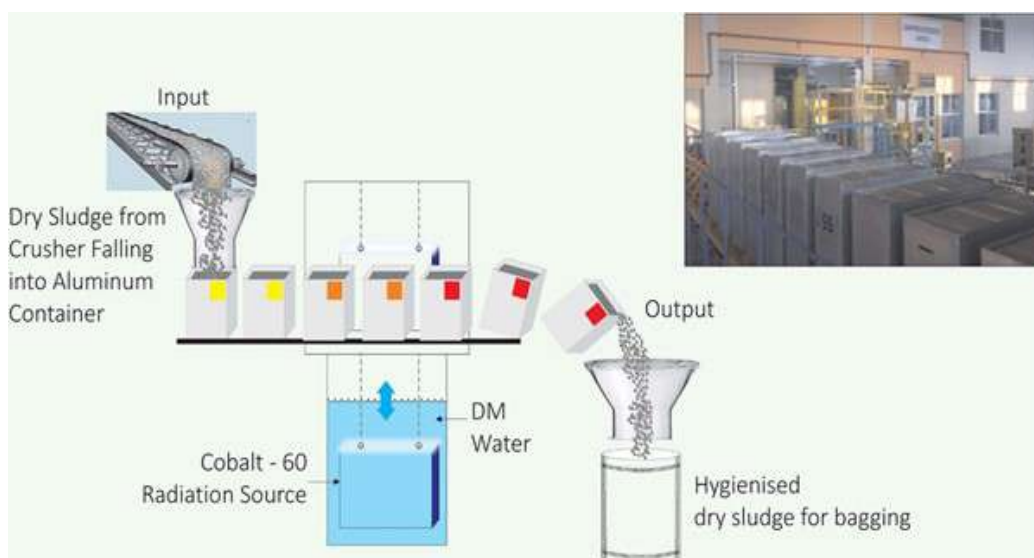


Figure 10: Schematic of radiation induced sludge Hygienisation

Advanced Radiation Hygienisation of Liquid Municipal Sewage Sludge @ SHRI

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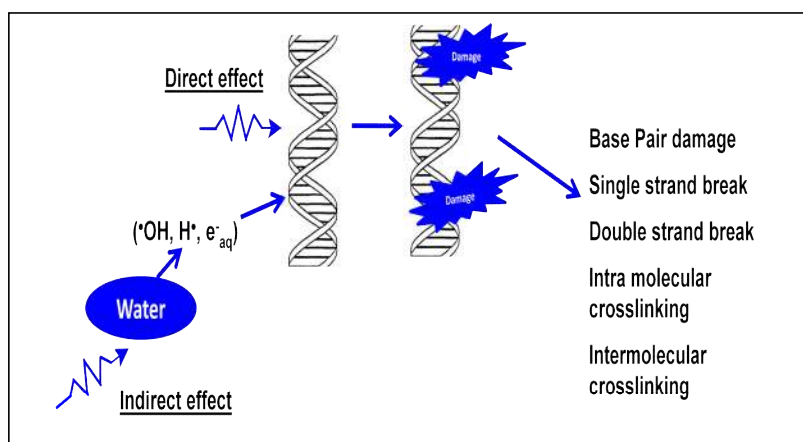
Sewage is the wastewater discharged from domestic premises consisting mainly of human waste which typically contains more than 99.9% water and about 0.1% solid. The solid waste present in the sewage is called sewage sludge. The sludge produced, though a rich source of many macro and micro nutrients for the soil, carries a heavy microbiological load and therefore its disposal has been challenge to the urban development authorities.

In recent years, interest in the use of sludge for application in agriculture has increased among the farming community as well as among the sewage treatment plant operators. The farming community has realized that the excessive use of chemical fertilizers is not conducive to sustained long term agriculture and sewage sludge can be beneficially utilized for supplying nutrients (N, P, K and micronutrients) to the crops, improving soil physical properties and above all increasing the soil organic matter. This can result in increased crop productivity as well as restoration of the soil fertility. For the sewage treatment plant operators, it offers a way of generating a value added by-product from the waste whose disposal otherwise is a matter of environmental concern. Thus, recycling of the sewage sludge to agricultural land can be an important outlet provided it is carried out in a manner that protects human and animal health as well as environment at large. The sludge after conventional treatment processes therefore still contains a heavy pathogenic microbial load and needs to be hygienized before application in the agricultural processes.

The ionizing radiation emitted by radiation sources such as Cobalt-60 interact with the critical molecules like DNA and proteins present in the cell resulting in the inactivation of the microorganism. In fact, this has formed the basis of producing radiation sterilized single use medical products which is now a well established industry worldwide including in India. On the same principle, the pathogens present in the sewage sludge can also be effectively removed from the sewage sludge by exposing it to high-energy radiation. Department of Atomic Energy (DAE) had set up a Sludge Hygienisation Research Irradiator (SHRI) at Vadodara, in collaboration with Gujarat Government and Vadodara Municipal Corporation, to demonstrate this technology. At SHRI, sewage is irradiated with gamma radiation emitted from a system of Cobalt-60 sources. A radiation dose of 3 kGy has been found to be adequate to reduce the microbial population by a factor of over 10^4 , thus reducing their concentration to less than 1000 per gram of the dried sludge as recommended for Class “A” sludge in the United States Environmental Protection Agency (US EPA). Sludge treated by radiation processing therefore will not add to the pathogen load of the environment and will not present any risk to the human, animal or crop health.

Hygienisation of sewage sludge using radiation

The Cobalt-60 (Co-60), produced artificially in nuclear reactors has a half-life of 5.27 years and emits two gamma rays of energies 1.17 and 1.33 MeV. The high-energy gamma rays emitted by Co-60 have ability to inactivate the pathogens with a very high degree of reliability in a clean and efficient manner. The ionizing radiation interacts directly and indirectly with DNA and proteins (Figure 1) present in the micro-organisms causing cell death. Indirect interactions are caused due to radiolytic products of water. Radiolysis of water results in the formation of highly reactive intermediates (OH radical, H radical and aqueous electron) which then react with the DNA culminating in the cell death.



Presence of oxygen enhances the radiation damage through formation of peroxides by fixing the radiation damage to cells thereby inhibiting their self-repair mechanism. The radiation treatment of sewage sludge offers an efficient, simple and reliable method to produce pathogen free sludge, which can be further upgraded to produce a value added bio-fertilizer. Thus, irradiation of sewage sludge as a tertiary treatment process provides a viable solution to the sewage sludge disposal and the important role it can play in providing organic matter and micronutrients to the soil.



Figure 2: Sludge Hygienisation Research Irradiator (SHRI) Facility, Baroda

Asia's first radiation treatment plant to hygienise municipal sewage sludge, Sludge Hygienisation Research Irradiator (SHRI), Vadodara, India was established by Bhabha Atomic Research Centre in collaboration with Vadodara Municipal Corporation and Government of Gujarat in 1992. It is an indigenously designed, technology scale demonstration plant with objectives to i) Establish the basis for radiation hygienisation of sewage sludge ii) Indigenously design, install and operate liquid sludge irradiator iii) Demonstrate compatibility with conventional sewage treatment plants iv) Study feasibility of utilizing municipal sewage sludge as manure and soil conditioners in agriculture v) Evaluate economic feasibility of the whole process. Figure 2 gives view of the plant.

The Process:

The SHRI plant consists mainly of three components namely:

- A cobalt-60 gamma energy source housed in an irradiation vessel
- Concrete-walled room for housing the irradiator and to provide biological shield
- A product handling system that moves sludge into and out of the irradiation vessel.

The radiation hygienisation of liquid sewage sludge is simple process where only one parameter the absorbed dose is to be optimised and assured. The process involves feeding of incoming liquid sludge into irradiation vessel and is circulated continuously in a closed loop for a pre-determined period to deliver the desired dose. After radiation exposure the treated sludge is withdrawn from irradiation vessel and pumped out to drying sand beds where the water evaporates yielding pathogen free dried sludge.

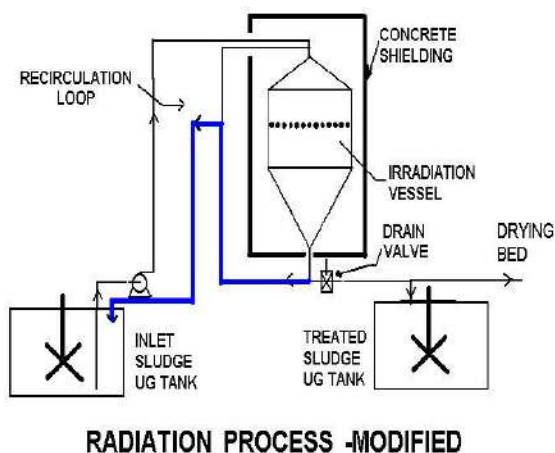


Figure 3: (a) Flow diagram of radiation processing unit at SHRI, Baroda and (b) Drying of Dose vs % Survival curve of sludge Hygienisation at SHRI Facility Badoda

The results show that a dose 3 kGy is adequate to reduce the total coliform counts by about 4log cycles. The operational experience of more than two decades of SHRI established that

~3kGy of absorbed dose deactivates ~99.99% of pathogenic bacteria constantly and reliably as shown in the figure (3).

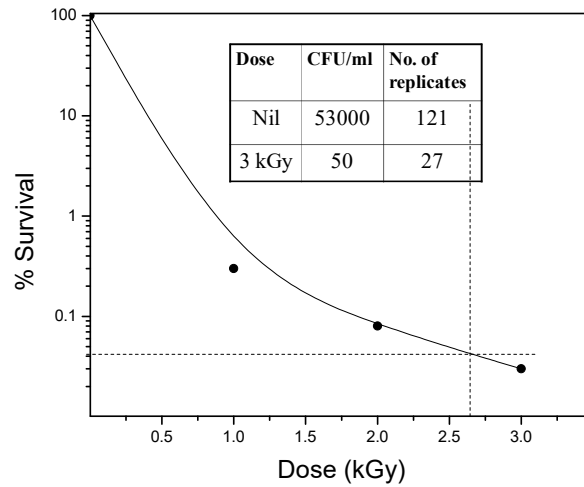


Figure 3: Dose vs % Survival curve of sludge Hygienisation at SHRI Facility Badoda

Since the irradiated sludge is free from bacteria, this can also be used as a medium for growing useful bacteria like rhizobium and azetobactor in the soil to produce bio-fertilizers, which can be used to enhance the crop yields. More than 5000 tons of sludge hygienised at SHRI facility has been used in different areas of Gujarat for large scale agricultural field trials in various crops in various seasons under a tripartite MoU between BARC, Krishi Vigyan Kendra (KVK), Vadodara and M/s Jupiter Agri-Inputs Corporation (JAIC), Vadodara. Figure 4 shows some pictures of field trials of hygienised sewage sludge. The trials conducted so far have shown that the radiation hygienized sludge based bio fertilizers are very effective in increasing the yields of many crops and can be utilized as organic fertilizer.

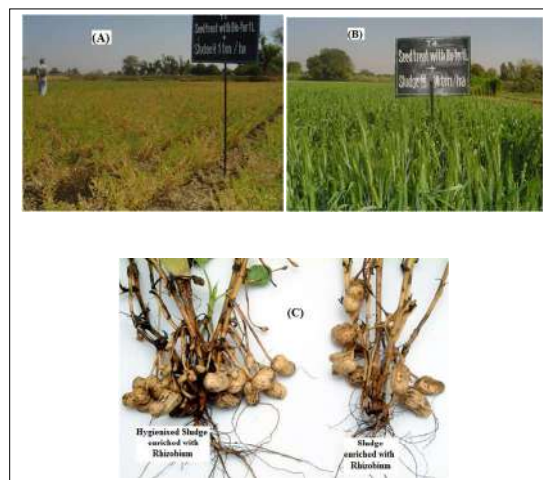


Figure 4: (A) & (B) Large scale field trials of hygienised

Conclusion

The radiation hygienisation of sewage sludge using gamma radiation from Cobalt-60 sources has been successfully demonstrated at the Sludge Hygienisation Research Irradiator (SHRI) facility in Vadodara, India. The process involves exposing the liquid sewage sludge to a radiation dose of 3 kGy, which has been found to be adequate in reducing the pathogenic microbial load by a factor of over 10^4 , making the sludge safe for agricultural applications. The irradiated sludge, free from harmful bacteria, can be used as a medium for growing beneficial bacteria like rhizobium and azetobactor in the soil to produce bio-fertilizers. Large-scale agricultural field trials conducted in Gujarat using the hygienised sewage sludge have shown promising results, with increased crop yields and the potential for use as an organic fertilizer. The radiation hygienisation technology offers a clean, efficient, and reliable method for producing pathogen-free sewage sludge, which can be further upgraded to produce value-added bio-fertilizers. This process not only addresses the challenges of sewage sludge disposal but also provides a sustainable solution for improving soil fertility and crop productivity. The successful operation of the SHRI facility for over two decades has demonstrated the feasibility and effectiveness of this technology, paving the way for its wider adoption in the management of sewage sludge.

Harnessing Electrons to Clean and Power the World

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The world must confront urban sprawl, industrial and municipal wastes, infectious diseases, foodborne disease outbreaks, chronic and acute water shortages, and securing adequate food supplies. With population increases and increasing urbanization cities around the world must manage enormous quantities of human waste. The spread of human and animal pathogens through improper disposal of wastewater and sludges is a global concern. The conventional view was that municipal wastes only require pasteurization to prevent the transmission of diseases and prevent environmental impacts. However, sewage sludges are also significant pools of water, energy substrates, and nutrients as well. These are grand challenges that require solutions that are technologically feasible, globally applicable, economically sustainable, and highly scalable.

Almost everyone in the water industry knows about UV and ozone disinfection processes. However, how many are aware of a technology that produces UV, ozone, and other highly reactive species as by-products of the process? We are referring to the portfolio of ionizing radiation technologies applying gamma, electron beam (eBeam) or X-ray sources. It is a sad commentary that even after X-rays were developed in 1895, environmental engineering textbooks even today hardly mention these technologies among those which are relevant to the water and wastewater industries. Ionizing technologies are those that pack enough energy to cause ionization events in matrices which contain microorganisms, and/or man-made organic pollutants including PCB's, PFAS, TCE, antibiotics, pharmaceutical, fermentation industry wastes. Even trace (ppm or ppb) levels of the pollutants can be effectively degraded. These ionization activities are so efficient that organic molecules that were once considered recalcitrant are now susceptible to even very low doses of ionizing technology. The use of ionizing technology, for example gamma irradiation for environmental applications is not new. Scientific publications dating back from the 1950's to the present have pointed out the value of this technology for various wastewater streams (*Lowe et al., 1956; Praveen et al., 2013, Chmielewski and Han, 2017; Wang et al., 2022*). This technology has been tried at laboratory and pilot scale in several countries including the USA, Germany, Japan, Poland, Canada, India, China, Austria, and the erstwhile Czechoslovakia. Table 1 is a summary listing the

pilot scale studies and full-scale projects which includes both gamma- based and eBeam technologies.

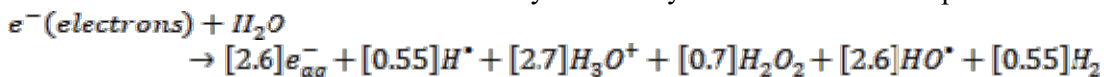
Table 1. Summarized listing of ionizing technologies used in the wastewater industry

Project	Location	Technology	Year
Deer Island Wastewater Treatment Plant -400m ³ /day	Boston, Massachusetts, USA	eBeam	1980's
Impela Project 2454 dry tons/year	Ontario, Canada	eBeam	1980's
Virginia Key Project 645 m ³ /day	Miami, Florida, USA	eBeam	1990's
Sludge hygienisation research irradiator (SHRI)	Vadodara, India	gamma	1990's
Mobile eBeam Demonstration Project	Daejeon, S. Korea	eBeam	2011
Dyeing Wastewater Treatment Project (2000m ³ /day)	Jinhua City, China	eBeam	2016
Dyeing Wastewater Treatment Project (30,000 m ³ /day)	Jiangmen City, Guangdong Province, China	eBeam	2020
Hospital wastewater treatment project (400 m ³ /day)	Shiyan City, Hubei Province, China	eBeam	2021
Antibiotic Fermentation Residues Treatment Project (200 dry tons /day)	Yining City, Xinjiang, China	eBeam	2021
Dyeing Wastewater Treatment Project (5000 m ³ /day)	Xiangyang City, Hubei Province, China	eBeam	2022
Landfill Leachate Treatment Project (300 m ³ /day)	Mianyang City, Sichuan Province, China	eBeam	2022

One of the reasons why the environmental industry has overlooked this powerful technology was probably because the original iteration of this technology was the use of radioactive cobalt-60 for generating gamma radiation as the source of ionizing radiation. However, times have changed. Today, when the world refers to ionizing technology, many are referring primarily to electron beam (eBeam) technology. There have been several technological advancements in this technology in terms of robustness and dependability that this technology is now routinely used in the sterilization of medical devices around the clock. The key highlight of this technology is its cost effectiveness. It is not that cobalt-60 is ineffective. On the contrary, cobalt-60 has been the work horse for over 65 years in saving millions of lives and bringing about economic prosperity in medicine, agriculture, and industry. The security concerns, however, associated with having a radioactive isotope in a wastewater treatment plant, the radioactive decay associated with isotopes, and most importantly the economics of acquiring the radioisotope cobalt-60 makes this technology not sustainable in the environmental industries much longer in much of the world. Other than in India (which subsidizes the cost of cobalt-60), eBeam is being considered as the technology of choice. Several US and international bodies have already funded research exploring the utility of ionizing technology such as electron beam for the destruction of organic pollutants such as microbial pathogens and man-made organic pollutants. In the US, the erstwhile Water Environment Research Foundation (WERF), the Strategic Environmental Research and Development Program (SERDP) and the US EPA have also funded extensive research to demonstrate the utility of eBeam technology for the destruction of PFOS and PFOA in solid matrices and liquid media including soils, effluent, sewage sludges and groundwater. There are several publications highlighting mechanisms of degradation and the usefulness of eBeam technology to degrade PFAS. The US Department of Energy published a comprehensive

workshop report detailing the technical specifications of the equipment needed to meet the needs of the environmental industry.

Electron Beam Technology- The primary difference between eBeam and gamma technology is that eBeam technology does not rely on radioactive isotopes. Rather it utilizes regular electricity to energize electrons in industrial scale equipment termed “electron accelerators” to as much as 10 million electron volts (10 MeV). These energetic electrons are extremely efficient at causing radiolysis of water molecules. The radical cation ($\text{H}_2\text{O}^{\bullet+}$) and pre-hydrated electrons ($\text{e}^-_{\text{aqueous}}$) formation is the primary process of radiolysis of water. Both reactions take place in the time scale of approximately 10^{-16} seconds. The cation radical quickly (in approximately 10^{-14} seconds) loses a proton to the neighboring water molecules forming the hydroxyl radical as follows $\text{H}_2\text{O}^{\bullet+} + \text{H}_2\text{O} \rightarrow \bullet\text{OH} + \text{H}_3\text{O}^+$. The hydroxyl radical ($\bullet\text{OH}$) is extremely reactive and is responsible for many of the beneficial attributes of this technology. The relative amounts of $\bullet\text{OH}$ and the $\text{e}^-_{\text{aqueous}}$ depends on the pH of the aqueous medium. Under highly basic conditions, $\text{e}^-_{\text{aqueous}}$ tend to predominate while $\bullet\text{OH}$ predominate under neutral or acidic conditions. In totality the radiolysis of water can be expressed as



where the values in parenthesis represent G values (number of species produced by 100 kV energy absorbed). Electron beam technology is paradigm-shifting because it uses regular electricity and simultaneously creates both reduction and oxidation processes *without the addition* of any chemicals. These powerful oxidation-reduction reactions occur almost instantaneously and can be characterized as an Advanced Oxidation-Reduction Process (AORP). Besides the reactive species, energetic electrons can also cause direct damage to organic molecules such as the DNA, RNA and organic pollutant molecules. Therefore, both the direct and indirect mechanisms make this technology extremely effective and time efficient.

The electron accelerators are commercial off the shelf equipment capital equipment. There are several types of accelerators such as Dynamitrons™, Rhodotrons™ and linear accelerators. There are North American, European and Asian manufacturers of this equipment. The different equipment is characterized by differences in the energy of the electrons that they can generate as well as differences in the power of the system. The electron energy (measured in million electron volts) will dictate the depth of water/sludge that the electron beam will penetrate while the beam power (kilowatt) determines the throughput of the system and the application parameter dose (measured in kilograys) indicates the energy deposited. There are several good reference texts that discuss these features in greater detail. Electron beam technology is not new. This technology is quickly becoming the go-to technology for the sterilization of medical devices, the pasteurization of foods, and for the phyto sanitary treatment of agricultural products when crossing international borders.

Electron beam technology is not only an efficient disinfection and environmental pollutant remediation technology, but studies suggest that it can be a disruptive technology to several commonly used technologies in the water and wastewater industry such as UV disinfection, ozone disinfection, and possibly thermal hydrolysis of sewage sludges. Studies performed in South Korea demonstrate that even at very low dose of 6 kGy, methane generation was at 231 m^3/day with only a 10-day residence time. The resulting sludge had reduced viscosity and dewatering was potentially improved. Preliminary studies suggest that the total cost per dry

ton of a 100 million gallons/day treatment plant using a 100-kilowatt eBeam system inclusive of mesophilic aerobic digester (MAD) was approximately \$293. Studies in Poland have also demonstrated the economic value of eBeam technology for sludge hygienisation and co-generation of methane. Detailed comparison studies are further needed to truly determine the cost effectiveness of eBeam technology compared to thermal hydrolysis.

Though there is a significant amount of empirical data to demonstrate the economic value and the technological effectiveness, there are no mega scale treatment facilities that employ this technology. Other than in China where there are operating eBeam treatment plants for treating industry and hospital wastewater, there are no functioning eBeam facilities in the west. There are possibly several reasons, the most important being that the environmental community rarely deploys a technology that they are not very familiar with. This lack of familiarity could be attributed to the lack of exposure of this technology in undergraduate and graduate curricula. There needs to be a concerted effort to socialize this technology amongst the environmental engineering consultant community. The global emphasis on sustainable technologies to address Sustainable Development Goals (SDG's) will require the environmental community to better understand this technology to harness electrons to clean and power the world of the future.

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Terra Preta (TP) production from septage for improving crop productivity

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Abstract

The lost nutrient rich top soil from the surface of the earth can be replenished by the use of organic fertilizers. Terra Preta (TP) is a high quality organic fertilizer with potential to replace chemical fertilizers (CF). This organic fertilizer has potential to compete with CF towards providing adequate nitrogen, phosphorous and potassium (NPK) to the soil as well as crops. The present study focuses on production of TP using septage sludge. This was then tested on seasonal different agricultural crops at field scale. Sites at Pimpalner district, Maharashtra were selected for the study and field experiments were conducted in two different seasons for one-acre capacity. At khariff season, *Oryza sativa* (paddy), *Zea mays* (maize), *Glycine max* (soybean) and rabi season *Triticum aestivum* (wheat), *Cicer arietinum* L. (bengal gram) were selected. Comparative studies were made for TP with CF on yield and other plant growth parameters. The use of TP on different seasonal crop has shown a 20-60% increase in yield. The increase in other parameters such as number of branches per plant was found to be 2-5% for TP, plant height up to 20-40% for TP. The yield obtained when TP was similar to that of the CF and among the organic fertilizer TP gives better yield. The second part of TP production using sludge procured from septic tankers was carried out at Baina, Goa. Field experiments were conducted for TP at Santa Cruz, Goa, India, for two different crops namely *Capsicum frutescens* (chili), *Oryza sativa* (paddy) and *Solanum melongena* (brinjal) with one-acre capacity. In this, standard recommended dose of CF and farmer's practice and TP were studied on yield and other plant growth parameters. The results of the study concluded that the use of TP increased yield by 15% and 16% for chilli and paddy respectively when compared to control. The increase in other parameters such as plant height and leaf length was also significant for TP with 15% and 10% respectively. However, for paddy the plant height was found to be 10.7% higher and 23% more biological yield. For brinjal, the CF results were more prominent than the TP.

Key-words: Terra preta, septage, organic fertilizer, crop productivity

1. Introduction

There is a high pressure on natural resources due to increasing population. About 854 million people in 46 countries are chronically hungry due to extreme poverty [1] and an estimated 2.2 billion people are suffering from micronutrient deficiencies. Unsustainable farming methods, such as monocropping and overuse of fertilizers and pesticides have resulted in extensive land degradation in India. A number of agricultural practices support the use of mineral

fertilizers. Its use results in water pollution and soil erosion, increasing acidification and salinization of soils. Monocropping is leading to depletion of micronutrients resulting in infertility of the soil. The average annual top soil loss in India is estimated be 16 T/ha. Population growth, intensified land use and climate change are increasing the pressure on agricultural land [2].

In developing countries, the increasing prices of chemical fertilizers coupled with growing concerns over sustainable soil productivity have led to renewed interest in use of organic manures as fertility-restorer [3]. Organic fertilizers are vital resources not only for supplying nutrients but also for replenishing organic matter content in the agricultural soils, particularly in the tropics. This would further emphasize the need to use organic fertilizers in soil fertility maintenance for sustainable crop production [4].

Terra Preta do Indio or “black earth” is a soil rich in organic matter. Terra Preta (TP) is the anthropogenic black soil that was produced by ancient cultures through the conversion of bio-waste and faecal matter into long-term fertile soils [5, 6]. These soils have maintained high amounts of organic carbon even several thousand years after they were abandoned [7]. It consists of dark humus probably derived from a combination of excreta (animal and/or human), charcoal (~10% of the soil), organic waste (mainly woody materials) and lacto-fermenting bacteria [8]. It is a living soil with very little leaching of nutrients, and a high water storage capacity. The man-made dark humus production in the TP process is much more efficient than the humus production that naturally occurs in nature. Therefore use of TP is a way to speed up the formation of fertile, organic rich and resistant soils [9, 10].

The major advantages of TP are that the production of these is cost effective since there is no energy consumption and does not demand any high temperature or pressure [11]. This organic fertilizer is capable of replacing the chemical fertilizers and are more feasible products generated from the waste, which serves the purpose of higher crop yield. As these serve as viable substitutes of chemical fertilizers, many studies have been already carried, although different agricultural crops can be selected to study their action on the same. Soil improvement had been further demonstrated by yield increases in several food crops, such as Rice, Wheat, Pigeon Pea and Chick Pea [12, 13]. Increasing soil fertility through above process will be more efficient compared to production of chemical fertilizers and its usage in terms of atmospheric carbon saved per unit of biomass [11]. The first part of the objective of this study was to produce TP from sewage sludge (additional advantage that it is a by-product and does not have separate manufacturing cost) respectively in Maharashtra. To test the produced organic fertilizers on the agricultural crops, three of the villages from Dhule district in Maharashtra, located in the north-western part of [Maharashtra](#) state, India were selected. It is situated on the banks of [Panzara River](#), with laterite soil (red soil) with pH of 7-7.5 [14].

The major focus of this pilot study was to produce TP, and study their effect on increasing soil fertility by comparing the crop productivity with CF utilizing the current practices at selected sites. TP production involves charcoal addition and lactic acid fermentation [15]. The pilot study consisted of two phases: One is the production of the products TP from sewage sludge was undertaken in Nashik, Maharashtra, India and the quality test of these products, followed by the field-testing on different crops in consecutive seasons’ i.e. kharif (2017) and rabi (2017-18). This included *Oryza sativa* (Paddy), *Zea mays* (Maize), *Glycine max* (Soybean) in kharif and *Triticum aestivum* (Wheat), *Cicer arietinum* L. (Bengal gram) in rabi season [16].

As a second part of the objective, TP was produced using the septage sludge procured from the septic tankers at Baina, Goa and to test the quality of the product. The second phase studied the effectiveness of TP produced on agricultural crops like *Capsicum frutescens* (chili), *Oryza sativa* (paddy) and *Solanum melongena* (brinjal) for improving the yield [16]. Santa Cruz town selected for the study located in central part of Panaji, capital of Goa, India. It is situated near the banks of River Mandovi with laterite soil (red soil) having pH of 5.5-6.5 [14]. The crops selected were based on the seasonal agricultural practices.

2. Materials and methods

2.1. Location of the study

The complete process of producing TP was carried out at wastewater treatment plant (WWTP) owned by Nashik Municipal Corporation (NMC) and transported to Manjri, Mohagoan and Shendwad villages located at Pimpalner village in Dhule district, Maharashtra, India with co-ordinates 54.192 N, 58.830 E for application of the same on agricultural crops.

For TP production, the septage solid was produced from Baina Sewage treatment plant, Baina, Goa, India (15.382855 N, 7.808210E). For testing the performance of TP, field experiments were undertaken at Santa Cruz, Goa, India (15.477727 N, 73.841090 E) in co-operation with BacTreat Environmental Solutions LLP funded by BIRAC, India.

2.2. Primary requirements

The sludge used was procured from the drying beds from WWTP, NMC, Nashik. Coco peat, charcoal and lactic acid bacteria were purchased from the local vendors in Nashik city. The *Eudriluseugeniae* species of earthworms were procured from the local farmers. Chemical fertilizers (Sufula, Di ammonium phosphate i.e, DAP and potash) were purchased from local vendors in Nashik city.

The sludge required for the preparation of TP at Goa was collected from the contents of night soil tankers. These tankers have a capacity of 8000-10000L each with solids varying between 4 to 6%. The solids and liquids were separated by leaving tank undisturbed for 24 hours. The liquid thus separated was collected in 1000L tanks, which were then sent to vertical flow constructed wetlands (VFCW) for the treatment. The thick liquor obtained at the bottom of the tanks was pumped to the unplanted drying beds to get the concentrated sludge. This concentrated sludge was then used to prepare TP. Charcoal and *Lactobacillus* culture was procured from the local vendors from Goa. The *Eudriluseugeniae* species of earthworms and press mud were procured from the local farmers. The CF (Urea, DAP and Muriate of Potash i.e MOP) were also purchased locally from Panaji city, Goa.

2.3. Preparation TP

The TP production was carried out in two-step process starting with lactic acid fermentation and then vermicomposting. For every 1000 kg of septage sludge, 15L of *Lactobacillus* culture and 100 kg charcoal were mixed to carry out lactic acid fermentation (LF) under anaerobic conditions. The lactic acid production reduces the pH, which helps in reducing the bad odour, and conserve dissolved soil organic matter for later humus formation. Charcoal in turn helps in increasing the pH and provides higher surface area for the microbes to attach and grow. After 15-20 days of lacto fermentation, the mixture was transferred to composting beds where it was mixed with press mud (press mud: sludge in the ratio 2:1) and selected strains of earthworms (*Eudriluseugeniae*) was introduced. Vermicomposting process was carried out for a period of 30 days. The procedure to prepare the TP is represented in Figure

1. Similarly, at Nashik, TP was produced with sludge from WWTP and coco peat was used instead of pressmud with all other steps remaining same.

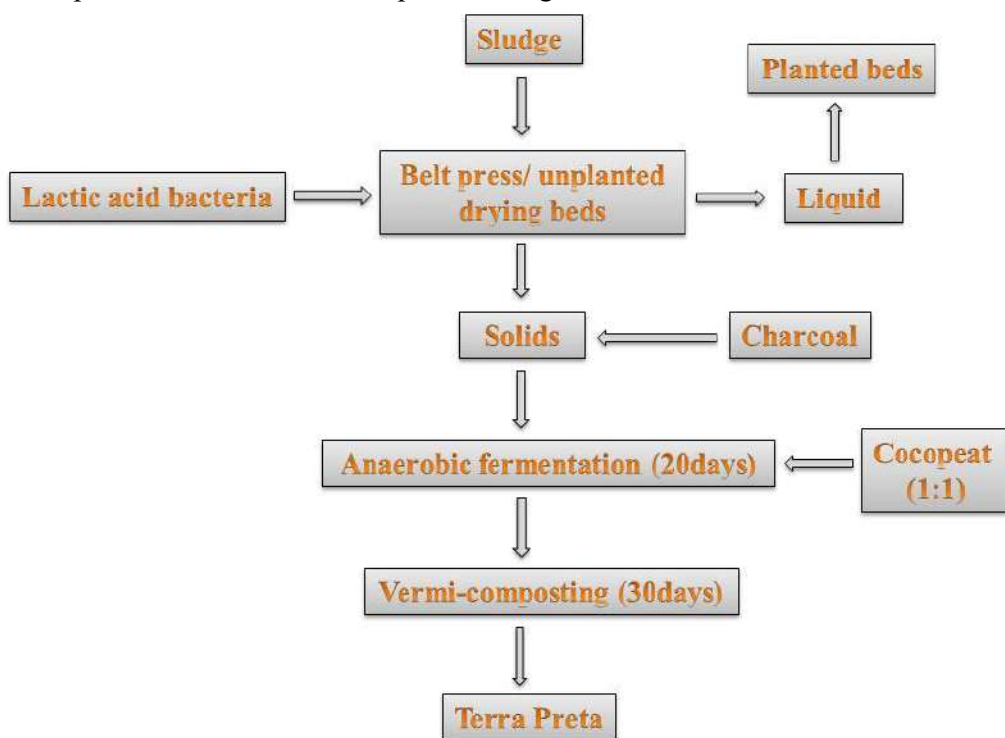


Figure 1: Process diagram for the preparation of TP

2.4. Treatment of liquid separated from the septage sludge using VFCW

A 20 m² VFCW was constructed with the focus to treat the liquid separated from the solids during TP production. The setup is of single stage as solids were aimed to be treated. The VFCW was filled with gravels of different sizes at three different heights from bottom to top. The gravel size of 10-40 mm constitutes the first layer of the bed with 20 cm thickness at the bottom, followed by 4-10 mm sized gravels with thickness 15-20 cm and finally 0-4 mm river sand for 40 cm height at the top. Perforated pipes were provided for ventilation at the bottom of wetland, which was extended vertically for 1m. The sand bed was planted with *Canna indica* [17-19]. Post solid separation the liquid from the septic tankers passes through the wetland for treatment. The quality of the septic tank water after separating solids and post VFCW treatment were analysed for different physico-chemical parameters.

2.5. Field application of TP at Nashik

Field trials of the above prepared TP were executed for two consecutive seasons (kharif, rabi). Rabi crops are agricultural crops that are sown in winter and harvested in the spring in India and kharif crops, which are also known as monsoon crops, are the crops which are grown during the monsoon or rainy season (June to October). The crops were selected based on the local agricultural practices namely wheat, bengal gram, paddy, soya bean and maize. Further crop selection was made according to the seasonal crop cultivation. The work was commenced kharif season with maize, paddy and soybean as selected crops for testing and in subsequent rabi season, wheat and bengal gram were chosen. The crops were treated with CF,

TP and control (without any fertilizer) as represented in Table 1. The CF used for the study was applied to the plots in a pattern similar to that of the farmers used them crop wise.

Table 1: Different treatments studied for field scale studies

No.	Treatments
1	Control with no application of any chemicals and/or organics
2	Recommended dose of CF
3	Farmer's practice of adding cow dung, municipal waste and poultry waste in the ratio 2:5:1
4	TP

The test plots were subsequently divided into 12 equal parts for 2 different fertilizers (CF, TP) and 1 control with 4 replicates. The nitrogen application rate was selected depending on the crop which corresponded to 60 kg of nitrogen/year/hectare. Randomized field trial technique was employed for cultivating crops with 16 plots for each crop study. The plots were provided with 0.3 m spacing with 15 cm intraplant spacing to avoid any possible mixing with the surrounding plots [20]. The calculations and the design for the field trial are as follows.

2 fertilizers x 4 replicates x 1 nitrogen application rate + 4 control = 12 plots

(<https://www.random.org/lists/>)

2.5.1. Kharif season

Total area of 2448 m², 3328 m² and 1152 m² of land from small land holding farmers were employed for paddy, maize and soya respectively to study effect of CF and TP on the growth and yield of the crops. The plots were divided into 16 equal test plots with 4 replicates for each treatment with a plot size of 151 m², 206 m² and 70 m² respectively for paddy, maize and soya., 1.05 T/acre of TP and 80 to 100 kg/acre of CF were applied to the test plots keeping blank as control with no fertilizer application. The crop was raised following usual agricultural practices as followed by the farmers.

2.5.2. Rabi season

In the consecutive rabi season, total area of 3632 m² and 928 m² of land were utilized for wheat and bengal gram with the plot sizes 225 m² and 56 m² respectively with similar test conditions as that of kharif season. Depending on the analytical report (considering the N content) 1.05 t/acre of TP were applied. Observations were recorded for days to maturity, number of branches per plant, number of pods per plant, plant height (cm), 100 seed weight (g), and seed yield per plot. Seed yield/hectare was calculated based on the net plot basis.

2.6. Field application of TP at Goa

Field application trials of above prepared TP were carried out on the agricultural plots at Santa Cruz. The crops chilli, paddy and brinjal were selected based on the local agricultural practices. Further crop selection was made according to the seasonal crop cultivation. The work was commenced on January 2020 until February 2021. The crops were tested with prescribed dosage of CF and TP along with the traditional farmers practice and control (without any fertilizer). The CF used for the study was applied to the plots in a similar pattern that the farmers used them crop wise. The CF application rate by the farmers is represented in the Table below (Table 2). The plot was divided into 18 equal parts for two different

fertilizers (CF, TP) and 1 control with 3 replicates with nitrogen application rate corresponding to 60 kg of nitrogen/year/hectare. Randomized field trial technique was employed for cultivating crops with 21 plots for each crop study. The plots were separated by 0.3 m spacing with 15 cm interplant spacing to avoid any possible mixing with the surrounding plots. The calculations and the design for the field trial are as follows.

7 treatments x 3 replicates = 21 plots (<https://www.random.org/lists/>).

During the test period, the plant height (cm) at regular intervals was recorded, by measuring the main shoot from the ground level up to the tip of the largest leaf stretched, along with leaf length (cm) and yield (t/ha).

Table 2: Composition of CF used crop-wise

Crops	N-P-K in kg/ha
<i>Triticum aestivum</i> (wheat)	50-24-24
<i>Cicer arietinum</i> L. (bengal gram)	20-40-00
<i>Oryza sativa</i> (paddy)	100-50-50
<i>Zea mays</i> (maize)	40-20-20
<i>Glycine max</i> (soybean)	40-20-12
<i>Capsicum frutescens</i> (chilli)	100-60-40
<i>Solanum melongena</i> (brinjal)	100-50-50

2.7. Statistical analysis

To compare the performance of TP with respect to the control and CF, statistical analysis was carried out using IBM SPSS Statistics 21 software to find out the correlation matrix between the parameters for different crops studied.

3. Results and discussions

3.1. Initial analysis of soil

The soil from both the test field was analysed for different parameters. Random sampling was done to collect the soil. The sample was sieved through 5mm mesh to remove the bigger stones. The results are tabulated in Table 3.

3.2. TP analysis

The produced TP was analysed for different chemical parameters to know the composition. The results were found to be within the FCO limits [21] for the compost produced and are tabulated in Table 4. The TP produced from WWTP sludge at Nashik exhibited 60% more TOC than the TP from Goa. The physical parameters such as moisture, particle size and bulk density were $28.78 \pm 13.88\%$, $94.56 \pm 2.24\%$ and $0.897 \pm 0.0601 \text{ g/cm}^3$ respectively for TP at Goa. The heavy metals such as Cadmium, Chromium, Copper, Nickel and Zinc were found 4.92, 42.62, 109.75, 38.13 and 792.41 mg/g. The Arsenic and Mercury were below the detectable limits for TP produced at Goa.

Table 3: Soil parameters in the study plots prior application of produced organic fertilizers

Parameter	Units	Nashik	Goa
Total organic carbon (TOC)	%	0.62±0.021	0.6133±0.0390
Available Nitrogen	kg/ha	229.85±21.3	202.11±17.44
Available Phosphorous	kg/ha	19.66±0.14	16.62±0.0164
Available Potassium	kg/ha	268.3±25.12	185.99±33.46
pH	-	6.78±0.0247	6.89±0.0241
Electrical conductivity	µS	365±9.23	137.9±6.22
Calcium	ppm	-	0.73±0.2264
Magnesium	ppm	-	0.83±0.0339
Available Sulphur	ppm	31.25±2.45	14.68±1.58

Table 4: Characteristics of the TP produced at Nashik and Goa

Parameters	Units	TP produced at Nashik	TP produced at Goa	Specifications (FCO 1985)
Moisture	%	60	28.78±13.88	25.0% max
Particle size	%	94.56±2.24 of the material passes through the sieve of 4.	94.56±2.24 of the material passes through the sieve of 4.0mm size	Min 90% of the material should pass through the sieve of 4.0mm size
Bulk density	g/cm ³	0.786	0.897±0.0601	<1.0
TOC	%	32.8	10.51±7.61	14% min
Total Nitrogen as N	%	2.31	1.18±0.6503	0.5% min
Total Phosphates as P ₂ O ₅	%	0.24	1.35±0.6836	0.5% min
Total Potash as K ₂ O	%	0.09	0.2261±0.217	0.5% min
NPK	%	2.64	2.77±1.35	3% min
C:N ratio	-	12.13	8.63±2.08	<20
pH	-	6.4	6.59±0.9438	6.5-7.5
Electrical conductivity	dS/m	3.76	3.44±1.31	<4.0
Arsenic as As ₂ O ₃	mg/kg	-	Nil	10
Cadmium as Cd	mg/kg	-	4.92	5 max
Chromium as Cr	mg/kg	-	42.62	50 max
Copper as Cu	mg/kg	-	109.75	300 max
Mercury as Hg	mg/kg	-	Nil	0.15 max
Nickel as Ni	mg/kg	-	38.13	50 max
Zinc as Zn	mg/kg	-	792.41	1000

3.3. Treatment of liquid separated from sludge using VFCW

The results for the treatment liquid separated using VFCW are tabulated in Table 5. The treatment of the liquid using VFCW has shown exceptionally good results where COD removal was found to be 93% with 73.3% of ammoniacal nitrogen removal.

Table 5:Physico-chemical parameters of liquid separated from sludge after VFCW treatment

Parameter (mg/L)	Filtrate	After VFCW
COD	161.63	11.43
Phosphate	50	4
Ammoniacal Nitrogen	74.3	19.8
Nitrate	27.3	7.6
Nitrite	9.3	1.6
Coliforms (CFU/ml)	$7 * 10^4$	$3.5 * 10^3$

The phosphates were found as low as 4 mg/L, which is insignificant. The nitrate and nitrite were found to be 7.6 and 1.6 mg/L. All the parameters were found to be within the CPCB discharge limits [22].

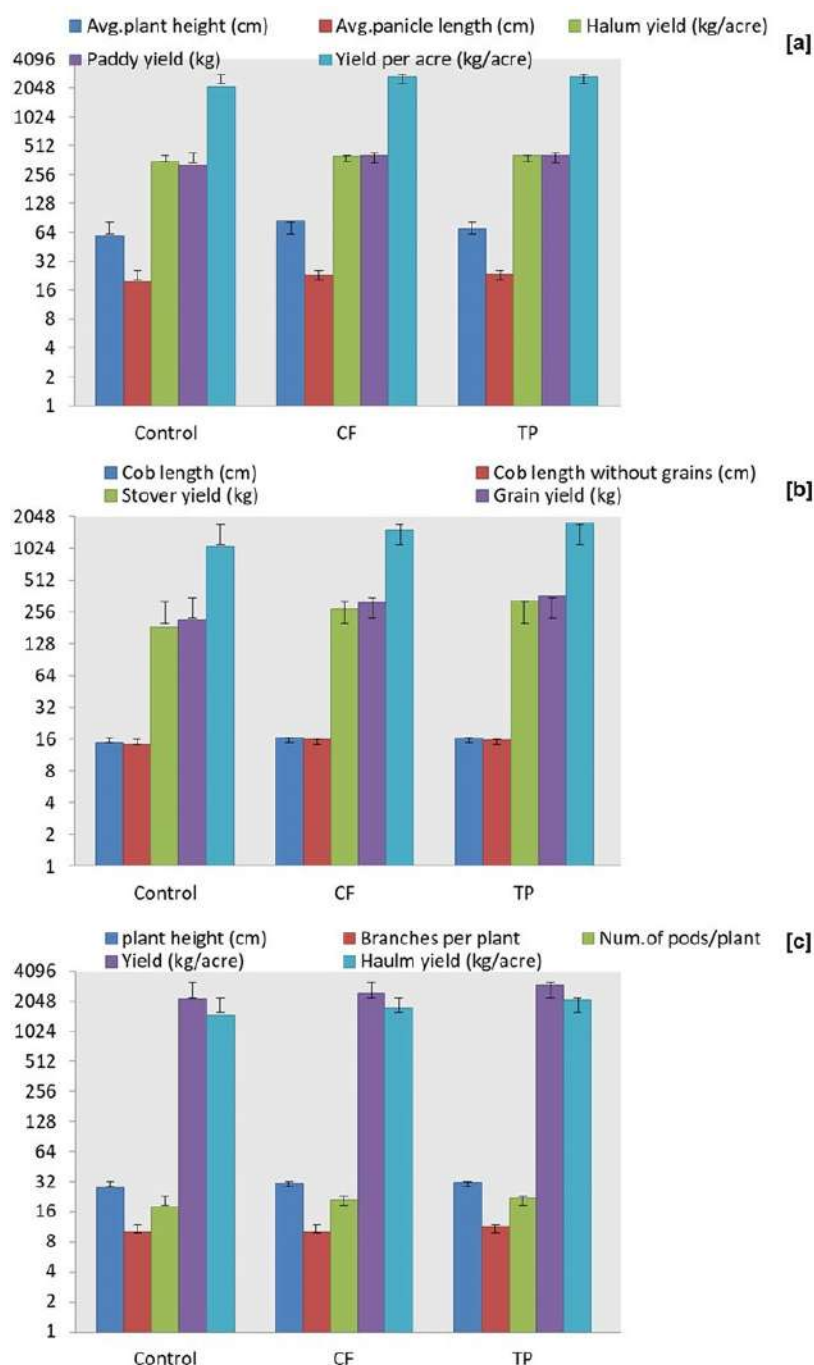


Figure 2: Representation of variations in different treatments on plant parameters of [a] paddy, [b] maize and [c] soya as kharif crops

3.4. Field trials at Nashik

Performance of different yield parameters associated with maize is given in Figure 2[b]. It was observed that the addition of compost boosted cob length significantly over control.

The lowest value of 14.83 cm for cob length was recorded for control, which increased with other subsequent treatments and obtained the highest value of 16.33 cm with CF followed by TP also the grain yield was significantly high with 1762 kg/acre for TP application. The

characteristics and TP tabulated in Table 4 which shows the presence of adequate amount of N and P with respect to the FCO guidelines [22]. Similar results were seen in case of paddy with highest plant height of 84 cm for CF and lowest value of 59 cm for control (Figure 2[a]). It was observed that the total yield was low for control. A small insignificant difference in the total yield between CF and TP were seen [23]. In case of soya, average number of pods/plants was significantly more for TP with 37, and lowest for control with 31.6 [24]. It was observed that application of TP resulted in higher total yield per acre as compared to control (Figure 2[c]).

For Rabi season, performance of different yield and yield-associated parameters for wheat is given in Figure 3[a]. It was observed that the addition of compost boosted height of wheat plants significantly over control. The lowest value for plant height of 78.225 cm was recorded for control which increased with subsequent treatments and obtained the highest value of 88.75 cm for CF [25]. Similar results were seen in case of bengal gram with highest value of 31.25 cm for TP and lowest value of 27.75 cm for control (Figure 3[b]). Average number of spikelet is highest with 28.85 for CF and control being the lowest with 27.45 spikelet per plant. Similar results have been seen for kernel length. In case of Bengal gram average number of pods per plants was significantly lowest for control with 17.85.

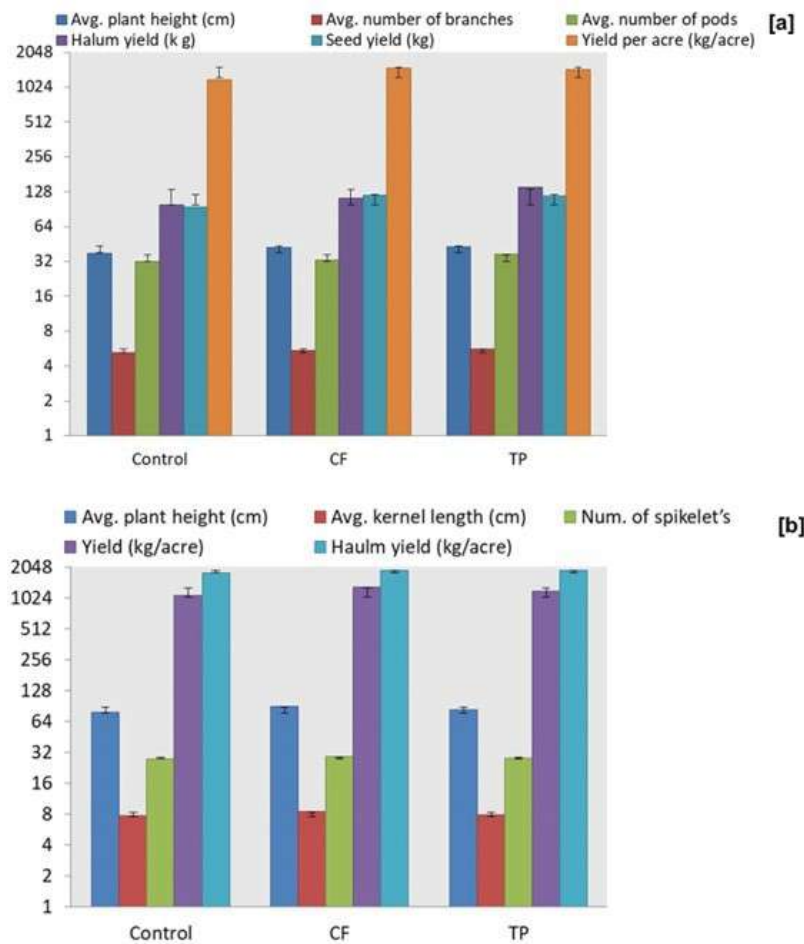


Figure 3: Representation of variations in different treatments on plant parameters of [a] wheat and [b] Bengal gram as rabi crops

Total biomass of Bengal gram and wheat increased significantly over control with the use of CF and TP at various levels. Total biomass of wheat showed very interesting trend as they show values with marginal difference (Figure 3[a]). The lowest value of 1800 kg/acre was recorded for control. Similar trend was seen for the grain yield as well (Figure 3[b]). Minimum yield 2173.9 kg/acre gram was noted in control [26].

3.5. Field trials at Goa

The Figure 4[a] represents the plant height comparison for different treatments for chilli. It was observed that the plants dosed with TP and farmer's practice were among the tallest as compared to the control and CF treated plants. For first 15 days of planting there was no observable difference in the plant height however the difference was significant at the 30th day.

A maximum plant height of 49.5 cm was reported for farmers practice and the lowest plant height 34.7 cm was noted for control while the other treatments were on par with farmers practice with an average plant height of 47.5 cm.

Further the leaves of chilli plants with farmer's practice grew very quickly and maintained their size while that of TP and mixed dosed ones showed gradual increase and achieved their largest possible sizes by day 45 and were considerably bigger than that of control and CF dosed ones. The leaf lengths of different treatments were compared with the CF. However, TP was comparable with CF at 4.9 cm. The yield generated by the plants dosed with the TP out performed that of control as well as CF dosed ones. The yield obtained for TP was heights with 5.2 t/ha followed by control.

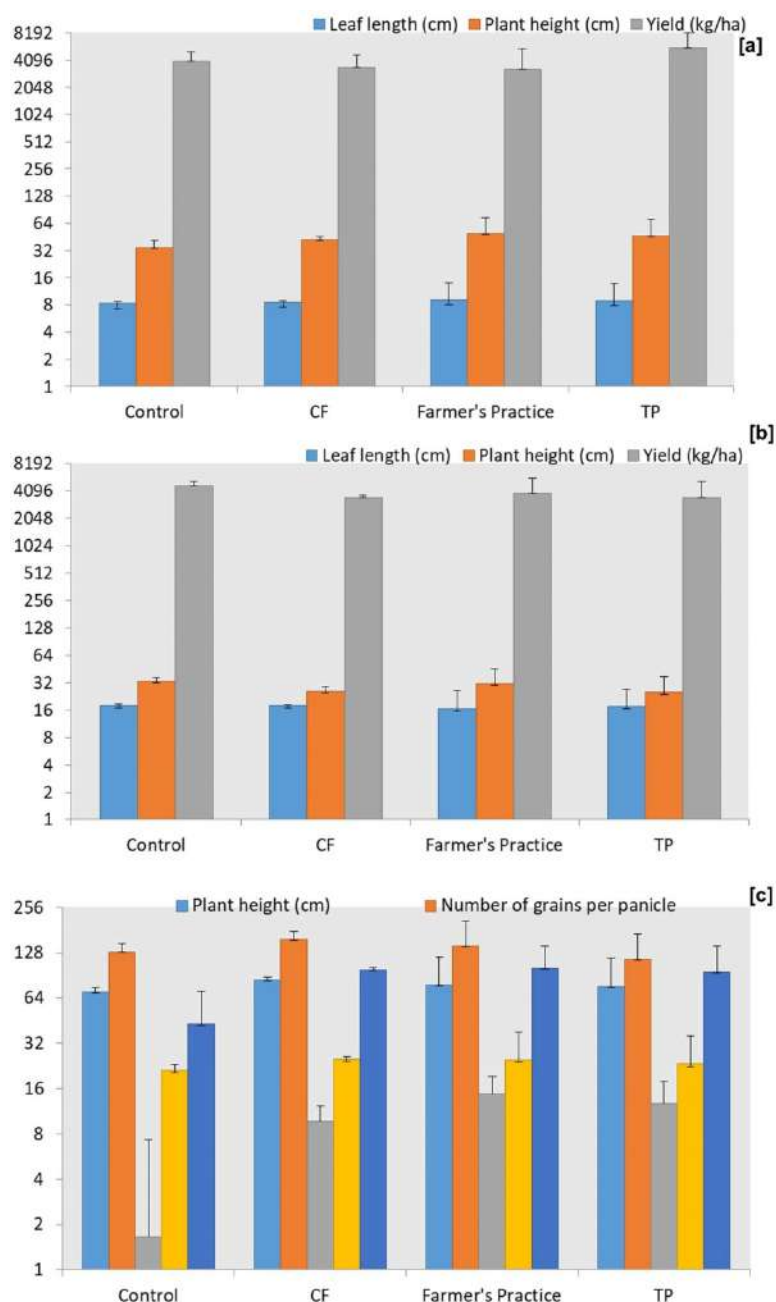


Figure 4: Representation of variations in different treatments on plant parameters of [a] chilli, [b] brinjal and [c] paddy

Figure 4[c] represents the comparison between the paddy yields for different treatments. It was observed that the yield was higher for TP with 25 t/ha than CF with 23.9 t/ha followed by farmers practice. The number of grains per panicle was higher for CF followed by farmers practice and TP. However, the total biological yield for TP was proportionate with CF and farmers practice as represented in Figure 4[c]. When the panicle length was compared for different treatments, it was observed that CF had highest length with 25.17 cm followed by farmers practice with 25 cm and TP with 23.33 cm. Figure 4[c] represents number of tillers per plant where the farmers practice had 14.7 tillers per plant followed by TP and CF with

14.7 and 9.7 tillers per plant respectively. The brinjal on the other hand did not show significant increase in either plant height or leaf length or the yield with TP. The control showed better results when compared with all other treatments as represented in Figure 4[b].

3.6. Statistical analysis

The statistical analysis was carried out to compare TP with CF for the different plant parameters. In case of kharif season for maize, paddy and soya, TP had a similar effect as that of CF, both of which varied significantly with control ($p < 0.05$) for the different parameters (Table 6).

In case of plant height a significant difference was seen for CF and different TP doses ($p < 0.05$) both of which also varied significantly with control ($p < 0.05$). In case of yield only TP was notably different from all the other treatments ($p < 0.05$). However, all the other treatments varied non-significantly with respect to control indicating a higher yielding potential for TP [27]. The paddy in Goa showed better plant height, biological yield and yield with $p < 0.05$ for all TP doses in comparison with CF. Brinjal on other hand did not showed increase in any plant parameters when compared to the control.

Table 6: A matrix with qualitative and statistical analysis of different fertilizers against crops

Treatment s	Wheat	Bengal gram	Maize	Paddy	Soybean	Chili	Paddy	Brinjal
Farmer's practice						+++	+++	++
CF	++	++	++	++	++	++	+++	++
TP	+	-	+++	++	++	+++	++	++
“+“ not significant, “++“ comparable, “+++“ significant								

In the Rabi season study, we conducted an investigation on the effects of different treatments on wheat and gram crops. It was observed a partial difference in terms of wheat yield, which suggests that there may be variations among the treatments. However, upon conducting statistical analysis, the results showed that the TP treatment, CF treatment, and the control group did not exhibit a significant difference [193]. Similarly, for bengal gram, the p-values obtained were very high ($p > 0.05$), indicating an insignificant difference between the treatments. This finding suggests that the treatments applied had no significant impact on the yield of bengal gram. One possible explanation for this lack of significant difference could be the residual effect of NPK fertilizers in the soil. It is likely that the soil still retained sufficient nutrients from previous applications, resulting in minimal variations among the treatments.

When examining plant height as a parameter, the statistical analysis yielded interesting results. A significant difference was observed for the CF treatment and different TP doses ($p < 0.05$). This finding indicates that these treatments had a noticeable effect on the height of the plants. Furthermore, both the CF treatment and the different TP doses showed significant variation from the control group ($p < 0.05$), suggesting that the treatments had an impact on the plant height. In terms of yield, only the TP treatment was notably different from all the other treatments ($p < 0.05$), indicating a distinct effect on the yield of the crops. However, all the other treatments did not exhibit a significant difference from the control group, implying

that they had a similar yield potential to the control group. These results suggest that the TP treatment had a higher potential for increasing yield compared to the other treatments [193]. In the context of paddy crops in Goa, noteworthy outcome were observed. The paddy crops treated with TP doses showed better plant height, biological yield, and yield compared to those treated with CF. The statistical analysis revealed a p-value of less than 0.05 ($p < 0.05$), indicating a significant difference in these parameters between the TP and CF treatments. This finding suggests that the TP treatment had a positive impact on the growth and yield of paddy crops in Goa. Conversely, when examining brinjal plants, the researchers found that the treatments did not result in any significant increase in plant parameters compared to the control group. This implies that the brinjal crop did not respond positively to the treatments applied and did not exhibit noticeable improvements in plant height or yield. These results highlight the importance of considering various factors when evaluating the effects of treatments on crop parameters and yield. It is essential to account for specific crop characteristics, soil conditions, and fertilizer treatments to obtain a comprehensive understanding of the findings.

4. Conclusions

The aim of this study was to treat faecal sludge in a sustainable manner. The conversion of this faecal sludge into TP will reduce the direct environmental impact on soil and water bodies. This treatment brings in the value addition to the product. The produced organic fertilizer showed all the parameters under the limits guided by FCO. The TP was found to be sterile from the microorganisms, such as coliforms, helminths and helminth eggs as the process of anaerobic fermentation and vermin-composting kills the residual microorganisms.

In the first season of this study (kharif) TP had produced higher yield than CF in maize and paddy though it was not higher in case of soya. However, the yield was comparable to CF in case of soya. In the second season of study (rabi), the TP showed better results compared to CF for bengal gram, but in case of wheat the yield was only comparable. Field trials with wheat and bengal gram were conducted during the rabi season and showed that addition of TP boosted bengal gram and wheat yields over control plants (without any fertilizer). Compared to plots where CF was applied, yield increase was comparable but not significantly, except for one case where bengal gram applied with TP showed highest yield. For both chilli and paddy, the TP has shown significantly good yield in comparison with CF and farmers practice. Not only the yield was higher, the data suggested that the quality of the crops in terms of plant height, leaf length etc. was on par with that of CF and farmers practice. However, brinjal showed no similar growth effects on the plants as that of other fertilizers and control. The liquid separated from the solids treated using the VFCW have shown exceptional results in bringing all the physico-chemical parameters within the limits for environmental discharge.

The lower p-values ($p < 0.05$) were seen for most of the crops which signifies that TP can be a potential alternative for environment friendly CF [27]. TP is not only organic, but also will be very effective in bringing the soil fertility up on frequent applications [28]. TP could be potential organic fertilizers, which can reduce the dependence on CF and helps in waste (septage) management. Not only that the TP produced from the waste can bring in the additional revenue as a value added product. These products incur less cost for the production and can be a cheaper alternative to CF.

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Enhancing Methane Production from Sewage Sludge: The Impact of Irradiation Pre-treatment on Anaerobic Digestion

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Abstract

Biogas production through anaerobic digestion is a sustainable method for managing organic waste and producing renewable energy. This process, which significantly mitigates methane emissions, leverages the high organic content of sewage sludge from wastewater treatment facilities. Recent advancements include the pre-treatment of sewage sludge with irradiation techniques like electron beam and gamma irradiation. These methods break down complex organic molecules in the sludge, enhancing its biodegradability and increasing the efficiency of methane production. This study examines the impact of irradiated dry sludge from the Ahmedabad Municipal Corporation on methane output in various treatment setups, employing Baroda liquid sludge as an inoculum. By determining the optimal balance of irradiated sludge volume, this research aims to optimize methane yields and advance biogas production processes, providing a robust solution for energy recovery from wastewater treatment operations.

Introduction

The generation of biogas and biomethane addresses two significant challenges faced by contemporary societies: the management of escalating organic waste and the imperative to reduce global greenhouse gas (GHG) emissions[1]. By transforming organic waste into renewable energy, biogas and biomethane production aligns with the principles of a circular economy, promoting the continuous use and reuse of resources while satisfying increasing energy demands and delivering broader environmental benefits.

Biogas serves as a versatile local source of power and heat, and as a clean cooking fuel, reducing reliance on traditional biomass in developing countries. Additionally, the residual "digestate" from biodigesters can be used as fertilizer, enhancing agricultural productivity and contributing to deforestation reduction. Upgraded biomethane, also known as renewable natural gas, is chemically identical to natural gas and can be seamlessly integrated into existing natural gas infrastructure, offering the same energy system benefits while being carbon-neutral.

Sewage sludge, a byproduct of wastewater treatment processes, is a particularly promising feedstock for biogas and biomethane production. The treatment and disposal of sewage sludge present significant environmental and economic challenges. Utilizing sewage sludge for biogas production addresses these issues by providing a renewable energy source while simultaneously reducing the volume of waste that requires disposal. This dual benefit enhances the sustainability of wastewater treatment facilities and contributes to the circular

economy. Furthermore, the anaerobic digestion process used to produce biogas from sewage sludge can be optimized through various pre-treatment methods, such as e-beam accelerators and gamma irradiation, to increase the yield and quality of the biogas produced. This paper evaluates the potential for sustainable growth in radiation technology assisted biogas and biomethane production using.

Biogas and Biomethane

Biogas is a mixture of methane (CH_4), carbon dioxide (CO_2), and trace gases produced through the anaerobic digestion of organic matter. The composition of biogas varies based on the feedstock and production pathway, typically including bio-digesters, landfill gas recovery systems, and wastewater treatment plants. Bio-digesters are airtight systems where organic material is decomposed by microorganisms, and contaminants and moisture are removed before the biogas is utilized. Landfill gas recovery systems capture biogas from decomposing municipal solid waste using pipes and extraction wells. Wastewater treatment plants recover organic matter from sewage sludge to produce biogas in anaerobic digesters.

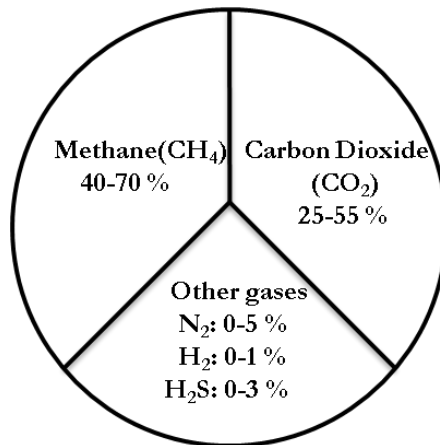


Figure 1: Typical composition of biogas

Sewage sludge, a byproduct of wastewater treatment processes, presents a promising feedstock for biogas production. The treatment and disposal of sewage sludge pose significant environmental and economic challenges[2]. Utilizing sewage sludge for biogas production addresses these issues by providing a renewable energy source while simultaneously reducing the volume of waste that requires disposal. This dual benefit enhances the sustainability of wastewater treatment facilities and contributes to the circular economy. The methane content in biogas ranges from 40% to 70%, with an energy content (LHV) between 16 MJ/m^3 and 28 MJ/m^3 . Biogas can be used for electricity, heat, or as a cooking fuel.

Biomethane, or renewable natural gas, is purified methane produced by upgrading biogas or through the thermal gasification of biomass followed by methanation[3]. Upgrading biogas involves removing CO_2 and contaminants, with water scrubbing and membrane separation being prevalent technologies. Thermal gasification converts woody biomass into syngas (carbon monoxide, hydrogen, and methane) at high temperatures and pressures, followed by

purification and methanation to produce methane. Biomethane has an LHV of approximately 36 MJ/m³ and is fully compatible with existing natural gas infrastructure and vehicles.

Biogas and biomethane production in 2018 against the suitable potential today

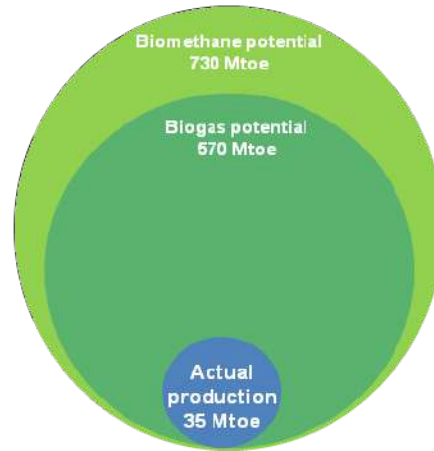


Figure 2: Biogas production gap

Sustainable feedstocks for biogas and biomethane production include crop residues, animal manure, municipal solid waste, wastewater, and forestry residues. Current production is around 35 million tonnes of oil equivalent (Mtoe), with the potential to meet 20% of global gas demand. Sustainable feedstock availability is projected to grow by 40% by 2040, with significant opportunities in Asia Pacific, North and South America, Europe, and Africa. This growth is driven by enhanced waste management and collection in the developing world.

Different Feedstocks Used to Produce Biogas and Biomethane

A wide variety of feedstocks can be used to produce biogas. The most common types of residue or waste are grouped into four broad categories: crop residues, animal manure, the organic fraction of municipal solid waste (MSW), and wastewater sludge.

Crop residues include materials left over from the harvest of crops such as wheat, maize, rice, other coarse grains, sugar beet, sugar cane, soybean, and other oilseeds. These residues are typically rich in organic matter and can be effectively converted into biogas through anaerobic digestion. Animal manure from livestock, including cattle, pigs, poultry, and sheep, is another significant feedstock for biogas production. Manure is abundant and contains a high level of organic material, making it an ideal candidate for biogas generation. Utilizing animal manure not only produces energy but also mitigates the environmental impact associated with its disposal.

The organic fraction of MSW encompasses food and green waste (such as leaves and grass), paper, cardboard, and wood that is not otherwise utilized (e.g., for composting or recycling). MSW also includes some industrial waste from the food-processing industry. Converting the organic fraction of MSW into biogas helps manage urban waste effectively while generating renewable energy. Wastewater sludge is semi-solid organic matter recovered in the form of

sewage gas from municipal wastewater treatment plants. Sewage sludge presents a particularly promising feedstock for biogas production due to its high organic content. The treatment and disposal of sewage sludge pose significant environmental and economic challenges. Utilizing sewage sludge for biogas production addresses these issues by providing a renewable energy source while simultaneously reducing the volume of waste that requires disposal, enhancing the sustainability of wastewater treatment facilities, and contributing to the circular economy.

Specific energy crops, such as low-cost and low-maintenance crops grown solely for energy production rather than food, have played an important role in the rise of biogas production in some regions, notably in Germany. Using waste and residues as feedstocks avoids the land-use issues associated with energy crops. Energy crops also require fertilizer (typically produced from fossil fuels), which needs to be considered when assessing the life-cycle emissions from different biogas production pathways. Using waste and residues as feedstocks can capture methane that could otherwise escape into the atmosphere as they decompose.

Most biomethane production comes from upgrading biogas, so the feedstocks are the same as those described above. However, the gasification route to biomethane can use woody biomass (in addition to MSW and agricultural residues) as a feedstock. This woody biomass consists of residues from forest management and wood processing.

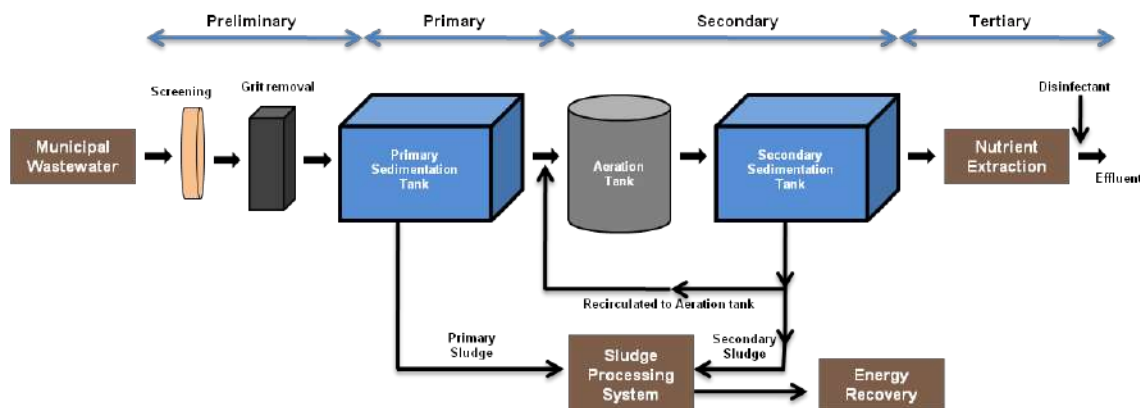


Figure 3: Typical sewage treatment plant

Sewage Sludge: A Product of Wastewater

The growing world population, alongside industrialization and excessive consumerism, has significantly increased wastewater production, particularly in urban regions. Improper disposal of wastewater is a global concern as it contributes to ecosystem pollution. These organic wastes, if not properly handled, can deteriorate water bodies, air, and soil. Currently, in many developing and less-developed parts of the world, waste disposal is often seen as the default option, contributing to environmental issues. However, indiscriminate waste disposal contradicts waste management efforts and handling hierarchies, where waste avoidance, recovery, re-use, and recycling are preferred to disposal. In light of this, various wastewater treatment approaches exist, and the choice of these is typically guided by a country's environmental policy.

Municipal wastewater undergoes preliminary treatment, which involves the addition of an acid or base for equalization and/or neutralization of the wastewater stream. Next, chemicals are added as coagulants before sending the waste streams to sedimentation tanks, oxidation ponds, and flotation tanks for primary treatment. The aim of this phase is to maximize the removal of suspended solids through mechanical methods such as centrifugation, coagulation, flotation, filtration, sedimentation, and gravity. The resultant solids from the primary treatment phase mark the first production of sewage sludge waste, conventionally known as primary sludge. The liquid product from the primary phase is then sent for secondary treatment to remove biodegradable and soluble organic matter through aerobic and anaerobic biological processes. Similarly, the secondary treatment process yields both solid and liquid products, with the liquid being sent for tertiary treatment and disinfection. The produced solid represents the second instance in which sewage sludge is produced, and this is typically referred to as secondary sludge.

At the tertiary stage, various technologies such as distillation, crystallization, precipitation, disinfection, filtration, coagulation, solvent extraction, and electrolysis are applied. The goal at this stage is to remove microorganisms, nutrients, and remaining suspended particles. The extraction of nutrients, which forms a crucial part of this stage, results in the production of tertiary sludge. It is worth mentioning that the resultant primary, secondary, and tertiary sludges vary in their properties (water content, energy content, and pollutants). Volatile solids are considerably localized in the primary sludge, while nutrients make up a significant portion of the secondary sludge.

Municipal sewage sludge presents a promising feedstock for biogas production due to its high organic content. Utilizing municipal sewage sludge for biogas production addresses significant environmental and economic challenges by providing a renewable energy source and reducing the volume of waste that requires disposal. This dual benefit enhances the sustainability of wastewater treatment facilities and contributes to the circular economy. The use of municipal sewage sludge for biogas production also supports waste management efforts by promoting the recovery and reuse of organic matter, thereby reducing pollution and supporting sustainable development.

General Sewage Sludge Composition

The composition of sewage sludge varies depending on the region, but generally, dewatered sewage sludge contains 50%–70% organic matter and 30%–50% mineral components, including 1%–4% inorganic carbon. It typically comprises 3.4%–4.0% nitrogen (N), 0.5%–2.5% phosphorus (P), and significant amounts of other nutrients, including micronutrients that could be recovered. For instance, phosphorus (P) is an extractable resource predicted to become scarce or exhausted in the next 50–100 years, making P recovery from wastewater an increasingly viable alternative. Despite its potential for nutrient recovery, sewage sludge's relatively low content of lignin and cellulose makes its organic matter easy to decompose. This rapid degradation can cause a sharp peak in nitrate and pollutant concentration in the soil if applied without pretreatment. The biggest challenge in utilizing sewage sludge lies in its contaminants, which include organic compounds (such as polycyclic aromatic

hydrocarbons (PAH), polychlorinated biphenyls (PCB), adsorbable organohalogens (AOX), pesticides, surfactants, hormones, and pharmaceuticals), inorganic materials (metals and their nanoparticles), and pathogenic species (such as bacteria, viruses, protozoa, and parasitic helminths).

Sewage Parameters: Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD)

When discussing sewage treatment, an important parameter to consider is Chemical Oxygen Demand (COD). COD measures the amount of oxygen required to oxidize organic matter in a sewage sample through chemical oxidation with a powerful oxidizing agent like potassium dichromate. COD is closely related to Biochemical Oxygen Demand (BOD), which measures the level of organic matter that can be biologically oxidized. The higher the BOD/COD ratio, the greater the oxygen-stripping capacity of the discharged effluent, indicating its potential to damage biological life in receiving waters. COD is usually higher than BOD because more organic compounds can be chemically oxidized than biologically oxidized. This includes chemicals toxic to biological life, making COD tests very useful for industrial sewage that might not be adequately captured by BOD testing. While COD testing takes approximately three hours, BOD testing requires five days.

In normal domestic sewage, the influent BOD is generally around 300 mg/l and is treated to at least 25 mg/l (as per European norms) before discharge to minimize pollution potential. Over time, a set ratio between BOD and COD can be established, allowing for quick feedback on sewage effluent pollution potential through COD testing. Advances in technology have enabled real-time monitoring of parameters such as COD, suspended solids (SS), ammonia, total nitrogen, and phosphorus, providing greater operational control.

Using chemical oxygen demand as a wastewater quality indicator, the total organic matter can be divided into biodegradable (BCOD) and inert (nonbiodegradable) fractions (ICOD). The biodegradable part includes readily biodegradable (RBCOD) and slowly/particulate biodegradable (SBCOD) components. The non-biodegradable fraction comprises soluble (ISCOD) and particulate (IPCOD) components. RBCOD refers to matter that can be quickly and easily degraded by microorganisms, such as volatile fatty acids or leachate from municipal landfills, while SBCOD decomposes slowly through various microbial metabolic processes. Both RBCOD and SBCOD must be hydrolyzed before destruction. IPCOD is insoluble and cannot be decomposed by microorganisms but is easily removable by sedimentation. ISCOD, however, poses a significant challenge to traditional wastewater treatment plants (WWTPs) due to the presence of persistent pollutants like organic, aromatic compounds (e.g., benzene, toluene).

Maximizing Biogas Production through Pretreatment of Sewage Sludge

Anaerobic Digestion Overview

Anaerobic digestion is a key treatment option for managing sewage sludge from municipal and industrial wastewater treatments. This process not only stabilizes sludge into reusable

biosolids but also generates renewable energy in the form of methane-rich biogas. Anaerobic digestion encompasses several metabolic reactions, including hydrolysis, acidogenesis, and methanogenesis, which break down biodegradable materials like food waste, livestock manure, and sewage sludge (Ss) into methane and carbon dioxide.

Types of Sludge and Digestion Dynamics

Three types of sludge are typically considered for anaerobic digestion: primary, waste activated (secondary) sludge, and a mixture of both. Primary sludge is inherently more biodegradable and hydrolysable than waste activated sludge. During hydrolysis, bacteria release extracellular enzymes to solubilize organic particulate matter, preparing it for subsequent digestion phases. However, microbial cells within flocs and extracellular polymeric substances (EPS) in sludge prove resistant to hydrolysis and digestion.

Pretreatment to Enhance Digestion

To overcome these challenges, extensive research has focused on pretreatment methods to accelerate the hydrolysis of organic solids into soluble organic matter. These methods aim to increase the quantity of soluble substrate, enhancing volatile fatty acid (VFA) production and, consequently, biogas yield. Additionally, pretreatment reduces sludge viscosity, allowing for higher solids concentration in digesters, which can optimize digestion times and reduce digester size. Common pretreatment techniques include ionizing radiation (e.g., electron beam or gamma), ultrasonication, ozonation, microwave, and thermal, acid, or base treatments.

Radiation Technologies for Sludge Pretreatment

Electron Beam Accelerator Irradiation

Electron beam accelerators propel negatively charged electrons to break down sludge components[3-5]. This process requires no additional chemicals and leaves no residual materials, making it an environmentally friendly option. The primary effects of electron beam irradiation include the production of reactive species such as hydroxyl radicals, which facilitate the breakdown of toxic and recalcitrant materials in sludge[6]. Key parameters of this technology include accelerating voltage, beam power, beam current, applied dose, and exposure time[6, 7]. Electron beam processing not only enhances biogas production but also improves digestate quality by increasing soluble COD (SCOD) levels, which benefits subsequent dewatering processes[4, 7].

Gamma Irradiation

Gamma rays, emitted from radioactive decay, are high-energy electromagnetic waves that initiate rapid reactions within sludge[5]. Gamma irradiation is primarily used for its pasteurization effects and has been adopted in Western countries as a disinfectant for wastewater and activated sludge. This treatment leads to the disintegration of sewage sludge, reducing total and volatile solids and altering floc size distribution. The rupture of microbial cells releases cytoplasm, increasing SCOD and enhancing the efficiency of subsequent

anaerobic digestion processes[5, 7, 8]. This results in increased biogas production and improved overall treatment efficacy.

Biomethane Generation from BioGold (Irradiated Dry Sludge from Ahmedabad Municipal Corporation)

In an investigation into the efficacy of methane production from sewage sludge, researchers utilized dry sewage sludge from the Ahmedabad Municipal Corporation, which had been irradiated at 10 kGy. This was compared against unirradiated sludge with a 4% solid content, using Baroda liquid sludge as the inoculum. The experimental design varied the volumes of dry irradiated sludge mixed with the Baroda liquid sludge inoculum. When 100 ml of dry

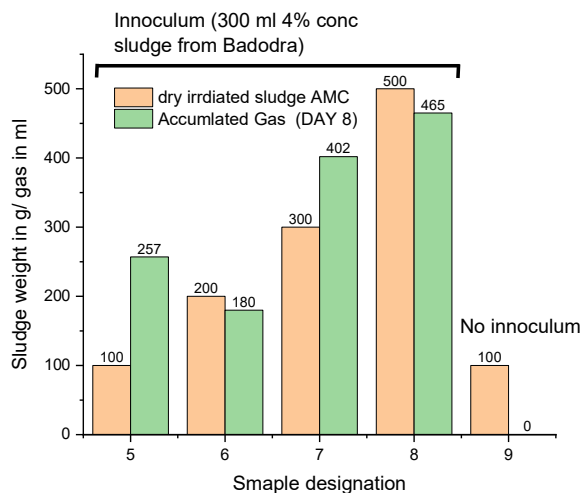


Figure 4 : Biogas produced in 8 days by using irradiated dry sludge

irradiated sludge was used, methane production reached 257 ml by Day 8. However, when the quantity of dry irradiated sludge was increased to 200 ml, methane production decreased to 180 ml, suggesting an optimal threshold for sludge volume. Further increases to 300 ml and 500 ml of sludge resulted in higher methane outputs of 402 ml and 465 ml, respectively, indicating a non-linear response to increasing sludge volumes. Remarkably, the control setup, which included only the Baroda liquid sludge without any dry irradiated sludge, showed no methane production, underscoring the essential role of irradiated sludge in facilitating methane generation.

These findings emphasize the importance of the quantity of dry irradiated sludge in the production of methane. There appears to be an optimal balance between the inoculum and the irradiated sludge that maximizes methane production, crucial for enhancing the efficiency of sewage treatment processes. Further exploration of biogas production using different sludges and inoculums revealed variations in biogas output. Employing 1000 ml of Baroda liquid sludge alone as the inoculum resulted in significant biogas production, totaling 1685 ml by Day 26, highlighting its effectiveness. In contrast, 600 ml of Biogas Plant inoculum yielded only 690 ml of biogas, indicating lesser efficiency. Interestingly, a mixed inoculum approach, combining 700 ml of Biogas Plant inoculum with 300 ml of Baroda inoculum, produced a

synergistic effect, leading to an increased total of 1455 ml of biogas. Additionally, incorporating 10g of MAC dry sludge into 600 ml of Biogas Plant inoculum increased the biogas yield to 840 ml, further demonstrating the potential of dry irradiated sludge to enhance biogas production even in less effective inoculum setups.

Gas Chromatography was utilized to analyze methane concentrations resulting from different irradiation levels applied to sewage sludge samples. The data reveal varying CH₄ yields across the treatment spectrum. At 0 kGy, the methane concentration was the lowest at 15%. A significant increase was observed at 3 kGy, where methane concentration peaked at 55%. However, further increasing the irradiation to 10 kGy led to a decrease in methane production, yielding 35% CH₄. These results suggest that while irradiation enhances methane output, there is an optimal level beyond which the efficiency may diminish.

Dose (kGy)	Methane (%)	Balance
0	15	Air
3	55	Air
10	35	Air

Conclusion

Radiation pretreatment can have significant impact on the biomethane potential. Optimal quantities of irradiated sludge are essential for maximizing methane yield, emphasizing the need to balance sludge volume for effective biogas generation. Additionally, the effectiveness of different inoculum types and their combinations suggests that tailored strategies could optimize biogas production. These findings provide valuable insights for designing and operating efficient and sustainable biogas facilities, leveraging strategic sludge and inoculum management to enhance energy recovery from wastewater treatment processes.

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Evaluation of irradiated biosludge under field conditions on Potato crop for soil health improvement

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Introduction:

Biosludges are obtained from municipal sewage systems and observed to be very good soil fertilizer as it contains high organic matter, nitrogen, phosphorus, and many trace metals essential to plants growth pointing to its potential in agricultural applications. However, they also contain a large amount of pathogenic microorganisms which can be a serious health concern. To make the use of sewage sludge as a safe valuable soil fertilizer in agricultural applications it needs to be disinfected. Radiation offers a very promising option for making sludge suitable for agriculture applications. The sludge obtained after irradiation has excellent nutrient quality and is applied to most fields to compensate for the removal of soil nutrients because of intensive cropping. This sludge provides an essential nutrient by slowly releasing them in top soil. They increase the porosity of soil there by promoting soil microbial population. These microbes ultimately make the nutrients available to the plant and thus increase the productivity of soil. Efforts were made to analyse this sludge and its application on the field to study its effects on Potato yield and soil health improvement.

Materials and Methods:

A field trial was conducted at 02 different locations during Rabi season (October to January) using randomized block design (RBD). The details of the locations and soil characters are given in Table No 1. Biosludge obtained from Ahmedabad Municipal Corporation project (Biogold) was used for experimental purpose. Doses of the biosludge includes initial dose: 20 tons /ha (200 kg per plot) followed by half quantity second dose at the time of earthing up (01 month). Both the doses were given by broadcasting method and mixed with the soil uniformly. Biogold was tested for its nutrient and heavy metal content before applying to the crop. Farm yard manure was obtained from farmer's field and used for application purpose.

Table 1: Details of field trial and soil characters used for experiment

No	Location	Plot size	Soil characters	Remark
1	Gulani village Tal RajgurunagarDist Pune. Farmer: RamkrushnaDherange	10 M X 10 M Taken in triplicate	pH: 6.8 EC: 1.1 μ S, OC: 0.64	Variety Jyoti
2	Kodit Bk village Tal SaswadDist Pune. Farmer: TanajiKhaire	10 M X 10 M Taken in triplicate	pH: 7.62 EC: 0.8 μ S, OC: 0.72	Variety: Jyoti

Results and discussion:

Soil and plant samples were taken before plantation, 01 months after plantation and at the time of harvesting and used for analysis of different nutrients and heavy metals as per standard procedure (Mehetre et al, 2008). Different Parameters studied were as follows...

1. Soil characters' change
2. Plant parameters
3. Heavy metal content of soil and plant
4. Microbial parameters of soil
5. Total yield

The details of organic carbon and nitrogen content of the soil are given in the table 2.

Table 2: Effect of biosludge on soil parameters.

Treatment	Organic carbon(%)		Nitrogen(%)	
	Before sowing	After harvest	Before sowing	After harvest
Biosludge	0.64±0.01	0.82*±0.12	0.058±0.01	0.086*±0.022
Farm Yard Manure	0.66 ±0.03	0.79*±0.14	0.062±0.012	0.078*±0.012
Control	0.65±0.032	0.45±0.11	0.086±0.014	0.078±0.014

The results showed significant change in the organic carbon and nitrogen levels with the application of biosludge and farm yard manure with respect to control plots. The results are in concurrence with the earlier studies reported in the literature (Crecchio et al. 2001, Mehetre et al. 2008).

The results of the microbial population studies with respect to amendments of biosludge comprising total bacteria, fungi, azotobacter and actinomycetes showed no significant difference in all the plots at the time of sowing but at harvest population dynamics changed due to various treatments. Bacterial population in all treatments plots was significantly different than in control plots. Biosludge treatment effects were significantly higher than those with FYM and control treatments. Fungal population was stimulated significantly by biosludge and FYM treatments. It has been reported that addition of organic matter leads to increase in microbial biomass and activity (Dhillon 1997, Kandeler et al. 1999). Biosludge provides continuous nutrients to the soil microbes which in turn help in plant growth. In a long-term field experiment on influence of organic manure (composed of wheat straw, oil cake and cottonseed cake) on soil fertility showed that manure added to a soil confer greater benefits for soil fertility and the soil environment (Meng et al. 2005).

Heavy metal content:

Potato samples harvested after 1 month and at the harvest of crop showed following results shown in Table 3. Analysis done by Atomic Absorption Spectroscopy.

Table 3. Heavy metal content of the potato plants (Values are mean of 03 replicates)

Heavy metal	Sewage sludge samples	Potato from control plot	Potato from biosludge treated plot (1 month)	Potato from biosludge treated plot (at harvest)
Cr	169.87±0.2	19.75±0.01	18.26±0.012	10.62±0.014
Cd	16.37±0.23	0.83±0.012	0.32±0.014	0.28±0.012
Ni	76.38±0.19	8.91±0.014	10.66±0.01	08.68±0.01
Pb	40.25±0.18	0.086 ±0.011	0.04 ±0.012	0.042±0.011
Zn	473.25±0.21	14.16±0.012	15.29±0.011	12.90±0.012

It was observed that the heavy metal content was observed in the biosludge but translocation to the plants and tubers was minimal. The effect of irradiated sludge on different crops was studied at NABTD and present results are in accordance with these studies (Athalaye et al, 2002).

Potato Yield: Yield data of the potato was compared with the control plots after harvest. There was 25% increase in the yield in sewage treated plot as compared with control. The details are given in the table.

	Potato yield in Control plot	Potato yield in sewage treated plot	Increase in yield
Yield/plot	200 kg	250 kg	25%

Effect of irradiated biosludge showed same results for the second potato crop taken in subsequent season at different location in Pune district. Thus the irradiated biosludge showed positive impact on soil as well as crop yield.

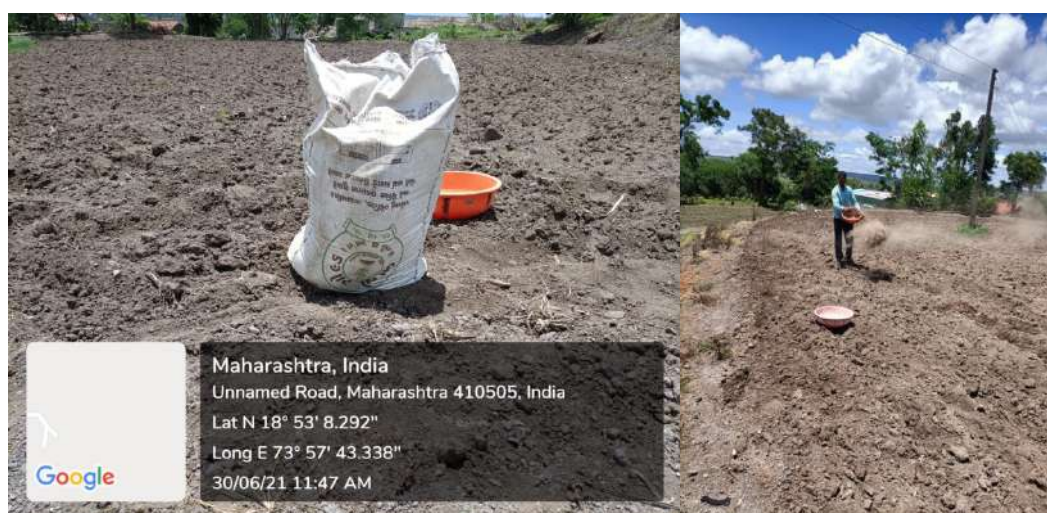


Figure 1: Location of the plot, application of biosludge



Figure 2: Representative Picture of the Potato plot from Pune District.

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Irradiated Sewage Sludge as a Nutrient-Rich Substrate for Agricultural Applications

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Abstract

The utilization of sewage sludge, a nutrient-rich by-product of wastewater treatment processes, as a soil amendment for plant growth has garnered significant attention in recent years. However, the inherent presence of pathogens and contaminants in sewage sludge poses a substantial challenge, necessitating developing and implementing effective treatment methods to ensure safe and sustainable utilization. This article delves into the potential of radiation treatment as a viable approach for sewage sludge hygienization and investigates its subsequent impact on plant growth and development. Comprehensive experiments conducted on diverse plant species, including moong bean (*Vigna radiata*), Red Amaranthus (*Amaranthus cruentus*), and chilli (*Capsicum annuum*), employing radiation-treated sewage sludge as a soil amendment, exhibited enhanced growth and development compared to control plants cultivated in the absence of sludge. Notably, the optimal sludge concentration for promoting plant growth exhibited variation contingent upon the specific plant species under investigation. These findings underscore the immense potential of radiation-treated sewage sludge as a safe and beneficial soil amendment for agricultural applications, fostering sustainable waste management practices and embodying the principles of the circular economy.

1. Introduction

Sewage sludge, a by-product of wastewater treatment processes, is a semi-solid material that contains valuable organic matter and essential nutrients such as nitrogen and phosphorus(1). These properties make sewage sludge a potential fertilizer or soil improver for agricultural applications. Waste water undergoes three generations of treatment: primary, secondary, and tertiary to produce sewage sludge (2). In primary treatment, solids are separated from raw sewage in primary sedimentation tanks, forming primary sludge. Secondary treatment involves biological processes, such as the activated sludge process or other biological treatments, which produce secondary sludge from the biomass generated during the breakdown of organic matter. Tertiary treatment includes advanced processes like chemical precipitation, filtration, or radiation treatment. Raw sewage sludge typically consists of 90-99% water and organic matters, including proteins, carbohydrates, and fats. It also contains pathogens such as bacteria, viruses, parasites, and other microorganisms. Nutrients like nitrogen, phosphorus, and potassium are present in sewage sludge, making it beneficial for agricultural use. However, the presence of heavy metals like cadmium, lead, and mercury, as well as chemical contaminants, poses environmental and health risks(3). Major treatment methods for sewage sludge include thickening, stabilization, dewatering, and disinfection(4). Thickening reduces the volume of sludge by removing a portion of the free water, while

dewatering further reduces the volume by removing water using centrifuges, belt filter presses, or drying beds.

Sewage sludge management is crucial for India due to several interconnected environmental, health, and economic factors. The country's rapid urbanization, industrial growth, and increasing population have led to significant challenges in managing wastewater and its by-products. The future prospects of sewage sludge management in India are promising, with the potential for resource recovery, energy generation, and sustainable agricultural practices.

Sewage treatment methods

Sewage sludge disinfection is a crucial step in the treatment process to ensure the safe disposal or reuse of sludge for various applications. The four main methods (**figure 1**) for disinfecting sewage sludge include radiation treatment, heat treatment, chemical disinfection, and biological processes(5). Radiation treatment uses ionizing radiation, such as gamma rays, electron beams, or X-rays, to inactivate pathogens in sewage sludge.

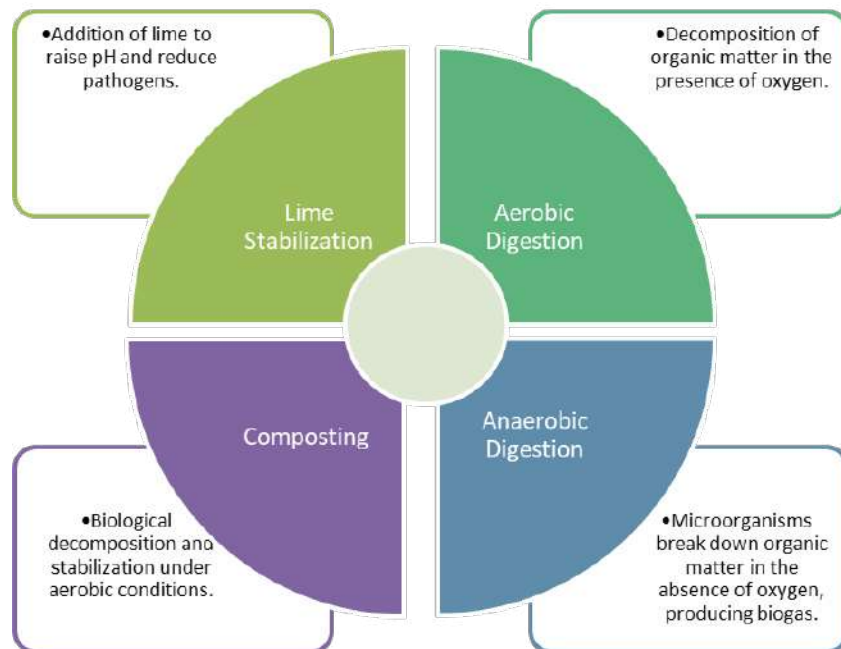


Figure 1: Type of sludge stabilization methods

This method is highly effective, has minimal impact on sludge composition and nutrients, and does not leave chemical residues. Heat treatment, such as thermal drying or pasteurization, applies heat to eliminate pathogens and can reduce sludge volume through evaporation. Chemical disinfection involves the use of chemical agents like chlorine, ozone, or lime to disinfect sewage sludge. This method is relatively simple, cost-effective, and can improve sludge stability but causes secondary chemical load. Biological processes, such as anaerobic digestion, composting, aerobic digestion, and vermicomposting, utilize microbial activity to reduce pathogens and stabilize sewage sludge(6). These processes are environmentally friendly, can improve sludge quality and nutrient value, and have the potential for biogas production and energy recovery. Table 1 shows a comparison of various processes used for sludge disinfection.

Table 1: Comparison of Disinfection Methods

Disinfection Method	Radiation Treatment	Heat Treatment	Chemical Disinfection	Biological Processes
Types of treatment	Gamma, electron beam, X-ray irradiation.	Thermal drying, pasteurization, incineration.	Chlorination, ozonation, lime stabilization.	Anaerobic digestion, composting, aerobic digestion, vermicomposting.
Description	Ionizing radiation (gamma rays, electron beams, X-rays) inactivates pathogens in sewage sludge.	Heat (thermal drying, pasteurization) eliminates pathogens.	Chemical agents (chlorine, ozone, lime) disinfect sewage sludge.	Microbial activity reduces pathogens and stabilizes sludge.
Advantages	Highly effective, minimal impact on sludge, no chemical residues, lower energy use.	Effective pathogen elimination, reduces sludge volume, stable product.	Simple, cost-effective, reduces odors, can be combined with other methods.	Environmentally friendly, improves sludge quality, potential biogas production, lower costs.
Disadvantages	Requires specialized equipment, high initial costs, public concern over radiation.	Energy-intensive, potential nutrient loss, odor generation.	Potential chemical residues, disinfection by-products, depends on dosage/contact time.	Longer treatment time, careful control needed, potential odor, may not eliminate all pathogens.

2. Radiation hygienisation of sewage sludge

2.1 Sludge Hygienisation Research Irradiator (SHRI), Vadodara

The Sludge Hygienisation Research Irradiator (SHRI) in Vadodara, India, is Asia's first radiation treatment plant for the hygienization of municipal sewage sludge. Established in 1992 by the Bhabha Atomic Research Centre in collaboration with the Vadodara Municipal Corporation and the Government of Gujarat, SHRI is an indigenously designed, technology-scaled demonstration plant. The SHRI plant consists of three main components:

- A Cobalt-60 gamma energy source contained in an irradiation vessel
- A shielded room for housing the irradiator
- A product handling system for sludge

Liquid sewage sludge radiation hygienization is a simple technique that requires only one parameter to be ensured and optimized: the absorbed dose. The process involves placing incoming liquid sludge into an irradiation vessel and operating it continuously in a closed loop for a specific duration to administer the intended dose. After radiation, the liquid sludge is transferred to sand beds, where water gets removed and transforms into pathogen-free sludge. *E. coli*, which is consistently found in sewage sludge, is used as an indicator organism to validate the effectiveness of radiation hygienization at SHRI. Over several decades of operation, SHRI has demonstrated that an absorbed dose of approximately 3 kGy consistently deactivates around 99.999% of harmful microorganisms. The radiation-processed sludge is odorless, and non-radiation workers can easily integrate the radiation hygienization plant with standard sewage treatment plants (STPs) and operate it in independent or combinatorial mode. More than 5,000 tons of sludge sanitized at the SHRI plant (**Figure 2**) have been used in large-scale agricultural fields in Gujarat for various crops and seasons (7).

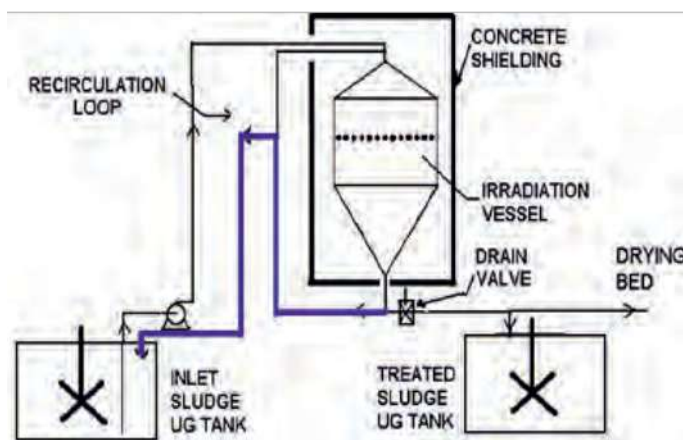


Figure 2: SHRI plant design

2.2 Dry sewage sludge hygienisation plant

The ability of high-energy radiation to kill pathogens has been implemented for hygienisation of dry sewage sludge dry through gamma irradiation.

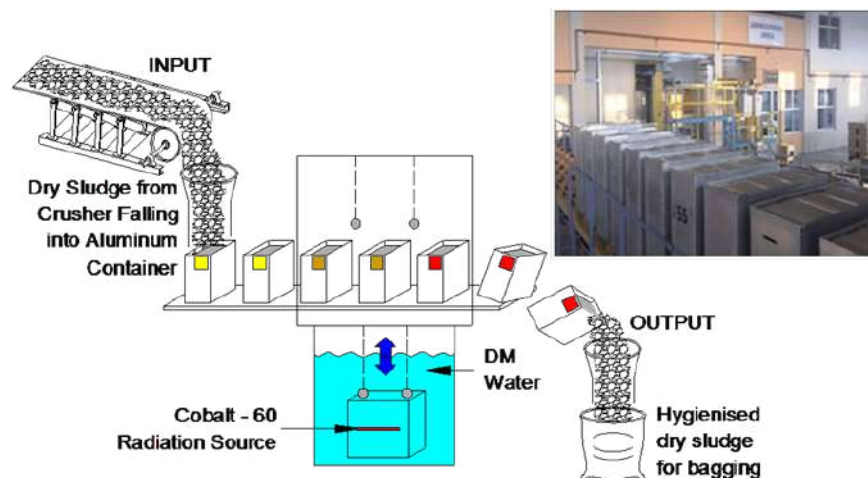


Figure 3: Schematic showing radiation hygienisation dry sewage sludge

The hygienised sludge is sprayed with a consortium of beneficial bacteria (Bio-NPK) to make it enriched organic manure. Based on this technology, the first technology demonstration plant of capacity ~100 tons/day has been designed, constructed and commissioned under an MoU between Ahmedabad Municipal Corporation (AMC) and BARC, Mumbai. With a ^{60}Co source strength of 300 kCi, the facility is operational since January 2019. Second such plant loaded with 150 kCi of Co-60 is operating at Indore under an MoU with Indore Municipal Corporation. Figure 3 shows process of hygienisation of dry sewage sludge.

3. Study of plant growth in radiation-treated sewage sludge

3.1 Study on Moong Bean Plant

A study was conducted to investigate the effects of radiation-treated sewage sludge on the growth of moong bean plants. Soil with varying percentages of sewage sludge (5% to 20%) was used as a growing medium for the plants (**Figure 4**). Initially, plant growth was found to be similar in all cases. After 6 days of sowing, all plant heights were in the range of 6-7 cm. However, after 20 days, the maximum growth (height-12 cm) was observed in the case of the highest percentage of sludge (20%) in the soil, while plants without sludge possessed a height of only 8 cm. Interestingly, after 40 days, plants without sludge grew only up to 12 cm, while the maximum growth (height-30 cm) was found in the case of 10% sludge in the soil. This suggests that the optimal growth was observed with 10% sludge in the soil, and growth decreased thereafter with increasing concentrations of sludge. Sewage sludge also had a significant effect on leaf size in moong bean plants. Plants without sludge had very small leaf sizes of (2.5 cm * 3 cm), while plants treated with 5% and 10% sludge had leaf sizes of (8 cm * 9 cm), indicating a substantial improvement in leaf development.



Figure 4: Growth of moong bean plant: left (control), right (with sludge 10%)

3.2 Study on Leafy Plant: Red Amaranthus

A study was conducted to determine the impact of sewage sludge on the growth of Red Amaranthus, a leafy plant. Sewage sludge was applied to the soil in four concentrations (10%, 20%, 30%, and 40%). The seeds of Red Amaranthus were sown in December 2023, with each treatment performed in triplicate. The two best plants from each treatment were chosen for the study, and four assessments were made over a span of 15 days. The results of this study indicate that the application of sewage sludge at various concentrations had a significant impact on the growth and development of Red Amaranthus plants (**Figure 5**).



Figure 5: Growth of Red Amaranthus plant: left (control), right (with sludge 20%)

3.3 Study on Fruit-Bearing Plant: Chillies

A similar experiment was performed using chiliseeds to investigate the effects of sewage sludge on fruit-bearing plants. The plants were sown in December 2023, with each treatment performed in triplicate. The two best plants from each treatment were selected for recording

observations. The results of this study demonstrate the favourable impact of sewage sludge on the growth and development of chili plants (**figure 6**).



Figure 6: Growth of chili plant: left (control), right (with sludge 10%)

Conclusion

The studies on moong bean, Red Amaranthus, and Chili plants highlight the potential benefits of using radiation-treated sewage sludge as a soil amendment for various types of plants. The optimal sludge concentration for plant growth may vary depending on the plant species and the specific growth parameters being assessed. Further research is needed to determine the long-term effects of sewage sludge application on plant health, yield, and the safety of crops produced for human consumption.

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Bio NPK (PGPB) consortium : A boon for soil health and organic farming

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Agricultural expansion in the current century is necessary to boost food output due to declining land resources and a rapid growth of human population. With the aid of chemical fertilizers, the first green revolution significantly increased food production, but attention to the sustainability of soil-ecosystem was ignored. In addition to harming the environment and human health, the use of chemical fertilizers has also reduced soil fertility with upset of ecological equilibrium. Indiscriminate use of the fertilizers by farmers has now resulted in threats of soil, water and air pollution with adverse effect on all living creatures. Due to the detrimental effects of decades-long chemical usage in agriculture, farmers and consumers alike are now shifting toward organic foods for health reasons. Biofertilizers and organic manures offer a new era to Indian agriculture holding a promise to balance many of the shortcomings of the conventional technology. Incorporation of biofertilizers or microbial inoculants in combination with organic manure can reduce the detrimental effects of current agricultural practices in an eco-friendly manner. Biofertilizers are not only effective for that particular crop enhancement in which they are used, but also increase the production of subsequent crops.

Organic farming is very much native to India since Vedas (10000B.C.). The sounds of the Veda and Vedic Literature are used to liven up the inherited capacity of crops to produce food bursting with the vigor of Nature's ability (like use of biofertilizers and organic manures) to create a healthy and economic approach to cultivate abundance of pure nourishing food for mankind. Growing evidence of soil degradation from excessive use of chemical pesticides and fertilizers has led to a reintroduction of the organic farming paradigm. "WHO" further conceptualized and advocated organic agriculture since late 19th century with formation of the International Federation of Organic Agriculture Movements (IFOAM) in 1972. The organic area in India is approx. 2.5 million hectares including certified forest areas and the global organic area is approximates 26 million hectares which also demand biofertilizers and microbe enriched organic manures for improvement of soil fertility in sustainable way. Moreover, year 2015 was declared by United Nations general assembly as International Year of Soils (IYS) and given slogan, "**Healthy Soils for a Healthy Life**".

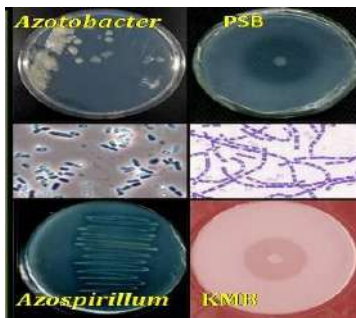
Plant Growth Promoting Bacteria (Biofertilizers)

Products containing living and latent beneficial microorganisms which enhance growth by mechanism of Nitrogen fixation, phosphate solubilization, potash and micronutrient mobilization etc. such as *Rhizobium*, *Azospirillum*, *Azotobacter*, *Acetobacter*, phosphate solubilizers and potash mobilizers can facilitate management of crop nutrients leading to long term sustainability in crop production. Bio-fertilizers are cheap inputs and very effective for Integrated Nutrient Management practice and organic farming.

Anand Agricultural University (AAU) has successfully developed and promoted, Anubhav Liquid Biofertilizers (LBF) comprising nitrogen fixers, phosphate solubilizers and potash mobilizers having minimum cell count of 5×10^8 / ml with shelf life above one year

suitable for field crops, drip irrigation and green house cultivation. These products are having bacteria of only one type meant for only one kind of nutrient augmentation hence further attempts made to develop consortium based multiple macro-nutrient supplying formulations.

- Liquid Biofertilizer Cultures are under Indian Patent deposits for from 2011. Bio-NPK Patent Published in Indian patent Journal No.50/2014 dtd. 12/12/2014.
- Plant Growth Promoting Cultures, Nitrogen Fixers and Phosphate solubilizers deposited at IMTECH (GOI), Chandigadh. Acces No. MTCC 5464 (*Azotobacter chroococcum*); Acces No. MTCC 5465 (*Bacillus coagulans*); AccesNo. MTCC 6567 (*Azospirillum lipoferum*).



Liquid Biofertilizers (PGPB) based Bio NPK consortium formulation saves minimum of 25% of N, P, K fertilizers, thereby reducing dependence on costly chemical fertilizers which ultimately assists in curtailing GOI subsidy input in Agriculture sector. Entrepreneurs who received AAU Bio NPK consortium technology under license (9) through public private partnership are emerging as key producers having production capacity of 2 to 3 lakh liters per annum and thereby benefiting the mankind and agriculture through this low cost agro input for farmers. Tribal demonstrations over thousands at farmer's field in Gujarat, 2003 to 2022 for Bio-NP (*Azospirillum/Azotobacter*+PSB) indicated that biofertilizer seed coating can save 25% NP chemical fertilizer with 8-10% increase in maize yield.

Sr. No.	PPP Organization / Entrepreneur	Year
1.	GAIC, Gandhinagar.	2015
2.	Ahmedabad Municipal Corporation, Ahmedabad	2017
3.	Margosa India Biogrow Pvt Ltd, Vadodara,	2018
4.	GUJCOMASOL, Ahmedabad,	2018
5.	Narmada Biochem Ltd., Ahmedabad	2020
6.	Indore Municipal Corporation Smart city Project, Indore, MP	2021
7.	AMUL–The Khaira District Cooperative Milk Producers Union Limited.	2022
8.	Banas Dairy, Plalanpur	2023
9.	KRIBHCO, Hazira, Surat	2024

Feasibility study for enrichment of hygienised dry sewage sludge with Plant Growth Promoting Bacterial consortium (Anubhav Bio-NPK) and to assess its efficacy in potato, tomato and wheat

- Field efficacy of hygienised sludge formulations showed significant increase in growth and yield parameters of tomato, wheat and potato plants as well as soil microbial population with clear indication that by using either Bio NPK consortium or hygienised sludge fortified with Bio NPK consortium along with 80% RDF remained

at par with chemical NPK supplement and indicated possible reduction (20%) of chemical fertilizers (RDF: NPK) in three test crops.

- Application of 200kg sludge in first year and 1000kg sludge in second year showed same trend for yield and related attributes measured for all three crops. Marginal yield increase is observed in five time increased application of sludge in test crops but simultaneously also increased heavy metal content and chromium metal found to increase with crossing the tolerance limit.
- Heavy metal content in tomato, wheat and potato which seems to be within permissible limit (as per Alloway (1990) and Shorrocks (1995) except chromium (Cr).

Campaign

Promote Bio NPK (PGPB) for Organic Farming

Get Sustainable Yield, Save Input Cost, Conserve Soil & Protect Environment

Phytoremediation of heavy metals from Soil and Sludge: An environment friendly approach

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Introduction

Owing to the fast industrialization and overpopulation during the last few decades, there has been a massive increase in xenobiotic components including metals in the environment. Due to various pollution exposures into the environment, the air, water, and land get contaminated. The excessive entry of these components into the environment leads to human and environmental health issues. Even at low concentrations, they affect plants, soil, humans, plants, and animals adversely due to their toxic nature.

Heavy Metal contamination in the Environment

Heavy metals (HM) are a group of naturally occurring elements that come from the earth's crust. However, various anthropogenic activities like mining operations, smelting, electronic industries, fossil fuel consumption, waste disposal and uses of agrochemical have resulted in the release of toxic metals into the environment. The concentration of heavy metals in soil, groundwater, and various water bodies is exceeding the acceptable limits in many countries as a result of unplanned urbanization, industrialization, population growth, and poor management policies leading to a threat to the human food chain (Sarker et al., 2022).

Metalloids and metals (e.g., Zn, Hg, Cd, Pb, and As) are considered heavy metals due to their high gravimetric density. When they are disposed of excessively in the environment as wastes, they can produce a variety of genetic anomalies, physiological and morphological problems, as well as carcinogenic effects, and increased mortality. Soils are considered as sink for heavy metals and heavy metal contaminated soil is a serious concern in most of the countries with respect to environment, human health and safe food production.

Remediation Strategies: Phytoremediation

There are various physical, chemical, and biological approaches which are being used to remediate heavy metal contaminations from soil and water, however, most of these methods are not environment friendly and expensive. Phytoremediation is one of the promising technologies to remediate heavy metals using potential plant species. It is a prominent green strategy having multifaceted advantages including eco-friendly facile, *in-situ* approach and inexpensive method (Song et al., 2022). It is operationally simple, aesthetically preferable, economically viable, and widely accepted and also improves the physical, chemical and biological qualities of contaminated soils. It is a complex phenomenon comprising mechanisms such as phytoextraction, phytoaccumulation, phytostabilization, phytovolatilization, and phytodegradation (Bhat et al., 2022).

The success of phytoremediation is determined by a number of environmental factors including soil properties, contaminant, chemical amendments applied, plant, climate, and geography. However, further research is warranted to understand the soil–metal–chelate–plant interactions in the rhizosphere and the mechanisms of plants absorbing, translocating, and accumulating heavy metals.

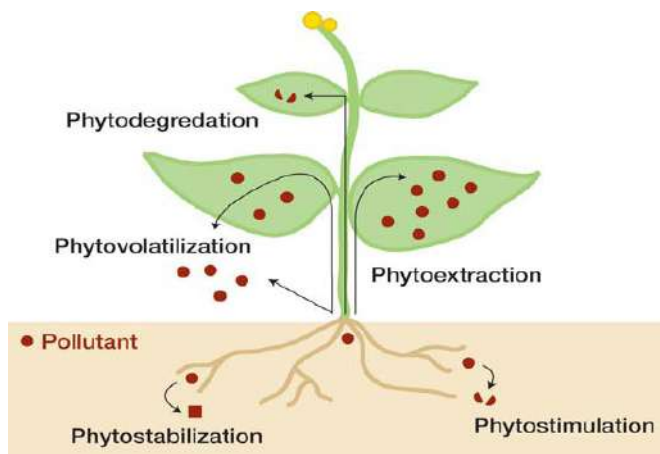


Fig 1. Processes involved in Phytoremediation

Phytoremediation of arsenic (Lab to Land): Our experiences

Arsenic (As) is a metalloid, whose contamination has been found to be spread over large areas in ground water and soil rendering the agricultural practices unsustainable in the affected areas. India is one of the major regions of the world where As contamination is prevalent; West Bengal is the most contaminated among Indian states. We have recorded higher levels of arsenic in water, soil, indigenous plants and crops from rural regions of West Bengal (Singh et al., 2021, 2023). The prolonged exposure of people to As through drinking water and food may lead to health problems of renal, respiratory and cardiovascular systems and can also induce cancer on through its mutagenic and carcinogenic effects (Rahaman et al., 2021). Use of As contaminated groundwater for irrigation in the contaminated field leads to As accumulation in the edible parts of crop plants and threatens sustainable quality production. Rice is the major crop in As affected West Bengal state and rice itself is most influenced by As contamination showing higher As levels in its grains. The need exists to devise *in situ* low-cost and sustainable methods for the remediation of contaminated soil and phytoremediation can be one of them.

Selection of plant is very crucial step while designing any phytoremediation strategy. For this purpose we have screened several plants and demonstrated the potential of *Vetiveria zizanioides* for arsenic remediation in hydroponic and simulated field conditions (Singh et al., 2017, 2021). Vetiver (*V. zizanioides*) is a herbaceous, perennial crop native to India having rapid growth and accumulates large biomass. Based on these findings, detailed field trials at two arsenic contaminated sites (Nadia and North 24 Parganas) in West Bengal were carried out in collaboration with Bidhan Chandra Krishi Viswavidyalaya and Jadhavpur University (W.B.). *V. zizanioides* plants were found efficient in arsenic remediation, leading to a decrease in arsenic levels to permissible levels. Further, rice was cultivated on these remediated sites

for two successive seasons and the rice plants grown in remediated field showed improvement in growth and yield parameters as compared to that of contaminated field. Arsenic concentration in roots, shoot, husk and grains of rice was found to be significantly lower in remediated field than in contaminated field (Singh et al., 2024). Therefore, phytoremediation using *V. zizanoides* can be a promising alternative to reduce As levels in contaminated soil leading to improved crop yield and lesser As levels in rice grains.

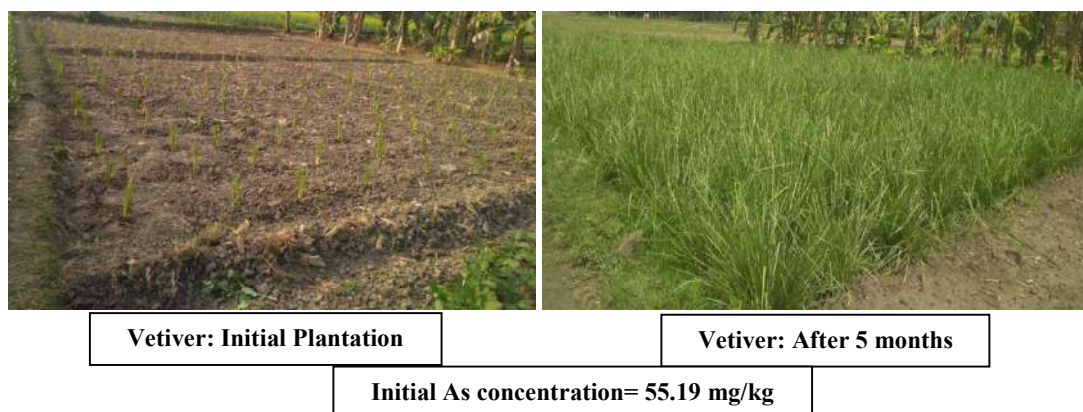


Fig 2. Phytoremediation trial carried out at Chakdah block, Nadia, WB (with BCKV)

Phytoremediation of HMs from Sludge: An alternative

With rapid urbanization, the amount of municipal sludge is increasing and its disposal has become an important issue in urban management. Sewage sludge is composed of high concentrations of organic matter (OM) and biogenic compounds, especially nitrogen (N) and phosphorus (P), which are necessary for plant growth. However, heavy metal contamination has been reported in the sludge at the global levels, posing a serious threat to the public health through food chain (Feng et al., 2023). The most common sources of heavy metals in sewage sludge are domestic and industrial wastewaters and corrosion of sewerage systems, as well as surface runoff from urbanized areas or roads. WWTPs may also receive wastewater from the agro-industrial sector, pharmaceuticals as well as body care and cleaning products. Moreover, illegal wastewater discharges are also an important source of sewage sludge pollution with heavy metals.

Therefore, heavy metal concentration in the sewage sludge should be thoroughly investigated and suitable remediation methods should be adopted. Phytoremediation may be a promising strategy and several plants have been identified for this purpose (Antonkiewicz et al., 2016; Singh et al., 2019; Salinitro et al., 2021). Further detailed trials are required which may lead to a higher efficiency of the process opening up new possibilities for the management strategies of sewage sludge.

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Organic fertilizers: A step towards sustainable agriculture

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Introduction

India overtook China as the country with the largest population in the world in the year 2022-23 with more than 142 crore people. Our nation is characterized by a broad diversity in climate, topography, flora, fauna, land use and socio-economic conditions. To help ensure food security in the future, agricultural systems will have to adopt different strategies. During the past 40 years, India has experienced remarkable land use and land cover changes including deforestation, crop land changes and urban expansion. Around half of the Indian Territory is used as crop land, making it one of the largest producers of agricultural commodities worldwide.

India has seen a vast increase in agricultural productivity over the last decades. Nevertheless, there are still significant yield gaps. The food production needs to be sustainably increased in the coming decades to address food security of the increasing population.

Thus, one of the main challenges facing over the country today is to develop sustainable solutions to increase the agricultural productivity. Various agricultural practices have been tried and tested including excessive/imbalanced use of chemical fertilizers, pesticides, herbicides and intensive ploughing. Although these practices have been proved effective in enhancing crop produce, concurrently have decreased the organic matter content of soil. In this scenario integrated nutrient management system 'INMS' can be envisaged as a solution.

Integrated nutrient management system (INM)

It refers to the maintenance of soil fertility and of plant nutrient supply at an optimum level for sustaining the desired productivity through optimization of the benefits from all possible sources of organic, inorganic and biological components in an integrated manner. The INM is based on the concept of regulated nutrient supply for optimum crop growth and higher productivity, improvement and maintenance of soil fertility, no adverse impact on agro – ecosystem quality by balanced fertilization of organic manures, inorganic chemical fertilizers and bio- inoculants.

The major factors of INM are the nutrient requirement of cropping system as a whole, soil fertility status and special management needs to overcome soil problems, if any, local availability of nutrients resources (organic, inorganic and biological sources) , economic conditions of farmers and profitability of proposed INM option , social acceptability , ecological considerations and impact on the environment.

The implementation of INM has a few advantages viz. it enhances the availability of applied as well as native soil nutrients, synchronizes the nutrient demand of the crop with nutrient supply from native and applied sources, provides balanced nutrition to crops and minimizes the antagonistic effects resulting from hidden deficiencies and nutrient imbalance, improves and sustains the physical, chemical and biological functioning of soil, improves the soil health and reduces nutrient losses to ground and surface water bodies and to atmosphere.

This system encourages the use of all the available sources of nutrients for crop production. A basket of balanced nutrition in INM would ideally consist of a chemical fertilizer, bio fertilizer, micronutrient fertilizer and organic fertilizer. Chemical fertilizers are being utilized as major sources of nitrogen, phosphorus and potassium. The most popular sources are urea (N 46%), various grades of complex fertilizers like N:P:K 15:15:15, 10:26:26 etc. Apart from the fertilizers containing primary nutrients, the Government of India is also promoting the use of slow release fertilizers to enhance the nutrient use efficiency and curb the losses of nutrients to the environment. In this endeavor of the Government of India, RCF Limited has played a pivotal and pioneering role in launching a slow release Sulphur coated Urea 'Urea Gold' recently. This product not only provides nitrogen to the extent 37% but also the very important secondary nutrient Sulphur to the tune of 17%.

The INM basket also contains the much required micronutrient fertilizers to address the 'Hidden Hunger' in the crops. The micronutrient fertilizers are fertilizers providing zinc, copper, iron, boron, manganese, and molybdenum. Most of the micronutrients are water soluble sulphate salts viz. zinc sulphate, copper sulphate etc.

Along with the chemical fertilizers the biological inoculants i.e. biofertilizers are also an indispensable part of the INM. Biofertilizers or Bio-Inoculants are formulations with live or latent agriculturally important microorganisms. There is a vast array of biofertilizers utilized by the farming community in India. The most popular being nitrogen fixing 'Azotobacter', phosphate solubilizing various bacterial / fungal strains and potash mobilizing 'Fratauria aurantia'. In order to address the depletion of organic carbon content in soil, the organic fertilizers and manures play a major role in INM. There is an enormous range of organic fertilizers available in the local markets. The Organic fertilizers are based on recycle of crop residue, biological waste etc. and can be reasonably named as '**brown gold**'.

Globally organic agriculture has been adopted by around 2.4 million farmers in area of 50.9 Mha which shares only 1.1% of total agricultural land. Moreover, with the crop intensification it is not possible to fulfill the nutrient demand through inorganic fertilizer alone, so 25-30 per cent of Indian agriculture's nutrient requirement must be met by different organic nutrient sources.

Organic fertilizers are mainly derived from animal or plant material which can change soil properties due to the abundance of organic matter and presence of both micro and macro nutrients. The popular organic fertilizers utilized in Indian agriculture comprise mainly of compost, vermicompost, manures, and innovative organic inputs phosphate rich organic manure (PROM) and potash derived from molasses (PDM).

Compost:

Compost is prepared from any biodegradable waste materials like straws, crop stubbles, crop residues, weeds, waste fodder, waste vegetables and other organic materials such as rice

straw, wood, saw dust, sugarcane trash and corn cobs etc. These organic materials are rich in organic carbon and there addition to soil improves the soil biological and physiochemical characteristics.

Table1 : Composition of Compost, FCO(1985) March 2023

Sr no.	Components	Specification
1.	Moisture, per cent by weight	Maximum 25
2.	Particle size	Min. 90% material should pass through 4.0 mm sieve
3.	Bulk density (g/cm^3)	<1.20
4.	Total Organic Carbon per cent by weight, minimum	12.0
5.	Total of Nitrogen (as N); Phosphate (as P_2O_5) and Potash (as K_2O) per cent by weight, minimum	1.2
6.	C:N ratio	<20
7.	pH	6.0-8.0
8.	Conductivity (as dm^{-1}) not more than	6.0
9.	Heavy metal content, (as mg/kg), maximum	
	Arsenic as (As_2O_3)	10.0
	Cadmium (as Cd)	5.0
	Chromium (as Cr)	50.0
	Copper (as Cu)	300.0
	Mercury (as Hg)	0.15
	Nickel (as Ni)	50.0
	Lead (as Pb)	100.0
	Zinc (as Zn)	1000

Vermicompost: It is product of quick semi-aerobic process where organic residues are converted into fine organic material by some specific earthworms. It contains higher level of nitrogen (1.0%), phosphorus (0.8%) and potassium (0.8%), and organic carbon to the tune of 18% (FCO (1985), Amendment November 2023). as well as presence of some hormones, enzymes and humic acids.

Vermicompost greatly enhances the root formation, elongation of stem and biomass production in many crops. It also enhances the soil physical properties like porosity, aeration, bulk density, drainage, water-holding capacity as well as other microbial activity of soil

Table 2 : Composition of Vermi- Compost, FCO(1985) March 2023

Sr no.	Components	Specification
1.	Moisture, per cent by weight	15.0-25.0
2.	Colour	Dark brown to black
3.	Odour	Absence of foul odour

4.	Particle size	Minimum 90% material should pass through 4.0 mm IS sieve
5.	Bulk density (g/cm ³)	0.7-0.9
6.	Total Organic Carbon per cent by weight, minimum	18.0
7.	Total of Nitrogen (as N) per cent by weight, minimum	1.0
8.	Total of Phosphate (as P ₂ O ₅) per cent by weight, minimum	0.8
9.	Total of Potash (as K ₂ O) per cent by weight, minimum	0.8
10.	Heavy metal content, (as mg/kg), maximum	
	Arsenic as (As ₂ O ₃)	10.0
	Cadmium (as Cd)	5.0
	Chromium (as Cr)	50.0
	Copper (as Cu)	300.0
	Mercury (as Hg)	0.15
	Nickel (as Ni)	50.0
	Lead (as Pb)	100.0
	Zinc (as Zn)	1000

Phosphate Rich Organic Manure (PROM)

PROM is an important alternative to nutrients for organic and conventional farming, which is prepared by processing a balanced mixture of organic residues, rock phosphate, oil cake, amino acids, humic acids and beneficial micro-organisms. It contains 8-10% phosphorus (P₂O₅) and organic carbon. PROM is included in the Fertilizer Control Order (FCO-1985) under organic fertilizers. The phosphorus in PROM is an organic alternative to expensive synthetic phosphatic fertilizers, which enriches the soil with phosphorus and other nutrients and keeps it friable for a long time. It gets decomposed by micro-organisms and increases the number of micro-organisms in the soil thus, enhancing the soil health index. PROM is known to improve water holding capacity of soil and maintain soil fertility. It enhances the immune system of plants, which makes plants healthy. The Government of India has taken initiatives to promote PROM on a large scale. To accomplish this vision, RCF Limited has taken the lead in establishing a commercial production unit of PROM at Trombay, Mumbai, Maharashtra during the year 2023-24. This plant with a capacity of 12000MT per annum is one of the first manufacturing units in a Public Sector undertaking. Generally PROM is applied at the rate of 50 to 100 kg per acre at the time of sowing in the field or at the time of ploughing, according to the fertility of the field and the requirement of the crop.

Table 3 : Composition of PROM, FCO(1985) March 2023

Sr no.	Components	Specification
1	Moisture, per cent by weight	15.0-25.0
2	Colour	Dark brown to black
3	Particle size	Minimum 90% material should pass through 4.0

		mm IS sieve
4	Bulk density (g/cm ³)	Less than 1.6
5	Total Organic Carbon per cent by weight, minimum	8.0
6	Total of Nitrogen (as N) per cent by weight, minimum	0.4
7	Total of Phosphate (as P₂O₅) per cent by weight, minimum	8.0
8	C:N Ratio	Less than 20:1
9	pH(1:5 solution)	6.5-8.0
10	Heavy metal content, (as mg/kg), maximum	
	Arsenic as (As ₂ O ₃)	10.0
	Cadmium (as Cd)	5.0
	Chromium (as Cr)	50.0
	Copper (as Cu)	300.0
	Mercury (as Hg)	0.15
	Nickel (as Ni)	50.0
	Lead (as Pb)	100.0
	Zinc (as Zn)	1000

Potash derived from Molasses:

This is a classic example of ‘waste to wealth’. The distillery waste is converted to potash rich fertilizer with 14.5% potash (K). This is one of the indigenous sources of potash in Indian agriculture. India currently imports 100% of the potash it needs for fertilisers, in the form of muriate of potash (MOP). The by-product of the sugar-based ethanol industry (PDM) can offer an alternative to the existing potash fertilisers. During molasses fermentation for ethanol production, a large volume of wastewater called “spent wash” is generated. This wastewater is rich in organic matter, inorganic salts, and other dissolved solids, making it highly polluting if released untreated. To comply with Zero Liquid Discharge (ZLD) regulations and minimise environmental impact, some molasses-based distilleries opt for incineration. The Incineration boilers (IBs) burn the spent wash at high temperatures, converting the organic matter into heat, flue gases, and ash as a by-product. The potash-rich ash has 14.5% potash content and can be used by farmers in the field as an alternative to Muriate of Potash (MOP, also known as potassium chloride, contains 60% potash content).

Organic Manure:

Animal Manure: Animal manure, such as chicken manure and cow dung, has been used for centuries as a fertilizer for farming. It can improve the soil structure (aggregation) so that the soil holds more nutrients and water, and therefore becomes more fertile. Animal manure also

encourages soil microbial activity which promotes the soil's trace mineral supply, improving plant nutrition. It also contains some nitrogen and other nutrients that assist the growth of plants.

Table 4 : Composition of Organic manure, FCO(1985) March 2023

Sr no.	Components	Specification
1	Moisture, per cent by weight	25.0
2	Colour	Dark brown to black
3	Particle size	Minimum 90% material should pass through 4.0 mm IS sieve
4	Bulk density (g/cm ³)	Less than 1
5	Total Organic Carbon per cent by weight, minimum	14.0
6	Total of Nitrogen (as N) per cent by weight, minimum	0.5
7	Total of Phosphate (as P₂O₅) per cent by weight, minimum	0.5
8	Total of potash per cent by weight, minimum	0.5
9	C:N Ratio	Less than 20:1
10	pH(1:5 solution)	6.0-8.0
11	Heavy metal content, (as mg/kg), maximum	
	Arsenic as (As ₂ O ₃)	10.0
	Cadmium (as Cd)	5.0
	Chromium (as Cr)	50.0
	Copper (as Cu)	300.0
	Mercury (as Hg)	0.15
	Nickel (as Ni)	50.0
	Lead (as Pb)	100.0
	Zinc (as Zn)	1000

Cow based liquid organic manure:

Now a days instead of sole application of cow urine or cow dung some cow based organic nutrient formulations such as Panchagavya, Sanjibani, Kunapajala, Amritpani, Beejamruth, Jeevamruth, Amritmitti and Amritjal etc. are used in agriculture. These liquid manures are nutritionally superior to cow dung/cow urine and rich in all essential macroand micro nutrient, plant growth hormone and vitamins etc. These liquid formulations are known for increasing crop yield, quality as well as enriching the soil. These organic nutrient formulations along with chemical fertilizers have exhibited synergetic effect on crop growth and development.

Wood ash extract:

Wood ash extract is prepared by weighing 10 kg of sieved wood ash into 50 litres of water in a plastic, thoroughly stirred with paddle every 3 days to enhance pro- per leaching of

nutrients up to 14 days. Thereafter, suspension is properly sieved to obtain clear suspension of the wood ash extracts .

De-Oiled cakes: De-Oiled cake are the solid residue obtained after extraction of oil from seeds and is being utilized as good organic fertilizer. For example, mustard, soybean, castor, Cotton seed oil cake etc. These oil cakes are rich in organic carbon (23%) nitrogen content (1.5%) which helps in plant growth and development.

Sewage sludge :

Sewage sludge is a residual solid, produced in the municipal water treatment. The digested sewage sludge has been documented to be 70% as efficient as monocalcium phosphate for phosphorous uptake. Sewage garbage waste and sewage sludge is known to increase 2/3 bar soil water percentage and lowered the bulk density . Silt loam amended with sewage sludge showed up to 20 times higher weight in water. Also addition of sludge compost to clay soil has been shown to reduce compaction and to increase the root depth. Sewage sludge compost is an excellent organic matter resource and soil conditioner. Addition of composted sewage sludge to soil improves the physical properties by (a) increase in water content (b) increase in water retention (c) enhancing aggregation (d) increasing soil aeration (e) improving permeability (f) increasing infiltration rate and (g) reducing surface crusting .Sewage and sewage sludge provide a vast resource of plant nutrients. RCF limited has established two municipal sewage treatment plants to take care of the process water requirements of the manufacturing plants. The sewage treatment plant details are shown in table 5.

Table 5 : Municipal sewage treatment plants at RCF Limited

Plants	Raw Sewage	Treated water(final product)	Sludge Generation
STP-1	22.75MLD	17.5MLD	1000MT/year
STP-2	20.215MLD	15.0MLD	3000MT/year

It is evident from the above table that the sludge generation is around 4000MT Per annum. The composition of sewage sludge is shown in table 6.

Table 6: Composition of Municipal sewage sludge (RCF Limited)

Sr. No.	Components	Specifications
1	Total Organic Carbon per cent by weight, minimum	38.0
2	Total of Nitrogen (as N) per cent by weight, minimum	0.9
3	Total of Phosphate (as P₂O₅) per cent by weight, minimum	
4	Total of potash per cent by weight, minimum	0.6
5	EC mmhos/cm	4.8
6	pH	6.4
7	Zinc (in ppm)	600
8	Copper (Cu) (in ppm)	300

9	Manganese (Mn) (in ppm)	250
10	Lead (as Pb) (in ppm)	135
11	Cadmium (as Cd) (in ppm)	120

Sewage sludge provides an opportunity to recycle the plant essential nutrients and organic carbon (OC) to soil for crop production. There are social and legal concerns of uncontrolled use of sewage sludge in agriculture due to potential problems of elevated transfers of heavy metal to the food chain causing threat to human health.

Impact of organic fertilizers on soil properties:

The soil organic matter is known to serve as soil conditioner, nutrient source, substrate for microbial activity, and preserver of environment. It is a major determinant for sustaining or increasing agricultural productivity. Soil fertility aspect controlled by soil organic matter include direct contribution of nutrients, influence on cation exchange capacity (CEC) and binding of heavy metals and pesticides. Soil organic matter is essential for development of a stable, aesthetic ecosystem on the reclaimed mine lands. Tropical Indian soils, majority of which belong to arid and sub arid climate rarely exhibit organic carbon levels exceeding 0.6 %. Overall the utilization of organic fertilizers improves the physico-chemical properties and soil health index.

Conclusion:

Organic farming has been globally accepted as the modern farming practices mainly to cope up with the soil and environmental degradation and also for sustenance of natural resources for present and future needs. Organic fertilizer sources such as compost, PROM, PDM, animal manure, sewage sludge, plant-based formulations etc. being the prime source of nutrients in organic farming have gained importance in the recent past. The use of organic fertilizers as a is a step towards Atmanirbhar Bharat and sustainable agriculture.

Way forward

The municipal sewage sludge is a rich source of plant essential nutrients mainly N,P,K, micronutrients and high content of organic carbon. Its safe application to soil for agricultural purposes will need some concerted efforts by the scientific community. The Research and Development department at RCF Limited is being working in this direction. To resolve the issues of heavy metals RCF Limited is eager to collaborate with Research bodies/ Institutes in India. This will surely pave way to introduce treated municipal sewage sludge as an supplementary or complementary source of nutrients and organic carbon in Indian agriculture.

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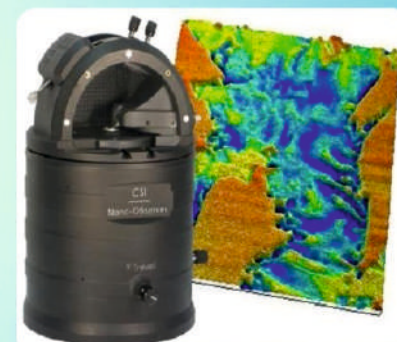
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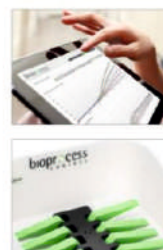
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