Trends in Radioactive Waste Management at Nuclear Power Plants (NPPs)

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Abstract:- An effective energy source is nuclear energy. Nuclear energy has been successfully used in various applications after years of arduous development, particularly in the area of nuclear electricity generation. The advantages of nuclear fuel include a high energy density as well as simple storage and transportation. However, as the number of Nuclear Power Plants (NPPs) increases, the issue of how to manage radioactive waste is becoming more and more significant. Removing nuclear waste is a challenging task. Nuclear power also generates relatively little waste since it can create a large amount of power from a very little amount of nuclear fuel. But because a lot of the radioactive waste produced contains radioactive substances, it needs to be handled very cautiously. Radioactive waste management refers to the appropriate handling, interim storage, and disposal of solid, liquid, and gaseous effluents discharged from NPP operations in order to protect people and the environment. Government agencies regulate the storage and disposal of radioactive waste to protect the environment and the general people. This study's goal is to discuss current trends in nuclear power plant radioactive waste management. This study covered the various management techniques for radioactive waste, including physical, chemical, and biological approaches. The study's key findings include the integration of digital monitoring systems to improve efficiency and safety, the growing use of sophisticated waste minimization techniques, and advancements in radioactive waste conditioning and packaging. Given the consequences of these developments, it appears that NPP operators are gradually shifting to waste management techniques that are safer, more effective, and ecologically friendly. This could greatly lower operating costs and long-term dangers. Furthermore, the paper emphasizes the increasing focus on sustainability and regional regulatory harmonization.

Key-words: nuclear, waste, radioactive, management, treatment, technology

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1 Introduction

Nuclear power plants play a significant role in the nation's energy system in many countries. Economically viable and clean for the environment, nuclear power compared to the majority of other energy sources utilized to produce power [1]. Along with them, it helps ensure the reliability of the nation's electrical supply. If the quality of living in industrialized nations of the world is to be maintained and the energy demands of developing nations are to be satisfied, it appears certain that a growing contribution to national energy supply from nuclear energy will continue to be required in the medium term and beyond.During the operation of a NPP, liquid, solid, and gaseous waste are produced that contain fission and activation products. Strict guidelines must be followed when handling, moving, storing, and disposing of radioactive wastes in order to safeguard the environment and the general public [2]. Through a radioactive decay process, nuclear waste progressively loses some of its radioactivity. The radioactive half-life is the length of time it takes for a radioactive substance to lose half of its initial radioactivity. To lessen the possible radiation risks to those handling and transporting radioactive waste, it is typically temporarily kept in an interim storage facility before disposal.

Building and implementing a secure, economically viable, and efficient system for the treatment, conditioning, and disposal of radioactive waste is essential to achieving compliance with the regulations. The public's acceptance of nuclear energy and its applications is thought to be significantly influenced by waste management. For the safe treatment of radioactive waste, technical solutions and technologies are essential. The criteria used to choose a certain waste management method may change depending on the preference of the organization, experience that has been gathered or is known, or the results of an optimization procedure [3-11]. It's important to manage radioactive waste from NPPs in a secure way. The radioactive waste management program is primarily focused on criteria for radiation protection. The major focus is to manage radioactive waste in a way that keeps radiation dosage limits for the environment, operating personnel, and the general public.Nuclear power also generates relatively little waste since it can create a large amount of energy from a very little amount of fuel. But because a lot of the trash produced contains radioactive materials, it needs to be managed very carefully.All phases of the nuclear fuel cycle generate some radioactive waste, and the cost of handling and discarding this waste is incorporated into the price of power.The operational organization/plant management must implement a nuclear waste management program to guarantee that the radioactive waste produced by the operation of NPPs is managed in a way that the aforementioned purpose is realized. This chapter's goal is to outline the various methods for managing radioactive waste produced by nuclear power reactors in a responsible manner.

Because the storage, treatment, and disposal of radioactive waste pose long-term environmental and safety hazards, managing this waste at nuclear power plants (NPPs) continues to be a significant problem. Many NPPs still struggle with waste volume reduction, safe containment, and adhering to changing regulatory criteria in spite of technological and regulatory advancements. In order to ensure sustainable nuclear energy production and safeguard public health, these issues must be resolved.

The following particular goals are the focus of this study, which attempts to examine current trends in radioactive waste management procedures at NPPs:
1. The identification and assessment of technological developments in packaging, conditioning, and waste reduction.
2. To evaluate the contribution of automation and digital monitoring to improving waste management safety.
3. To examine how operational procedures in various locations are affected by regulatory frameworks.
4. To investigate potential future paths for the economical and sustainable management of radioactive waste.

The study aims to offer practical insights for researchers, operators, and policymakers who are striving toward better radioactive waste management by concentrating on these goals.

Despite technological advancements, a number of gaps persist:

- Lack of a Unified Global Strategy for HLW: In many nations, there are no widely agreed-upon solutions for the long-term disposal of high-level waste (HLW), particularly wasted fuel.
- Limited models designed to account for regional geological, hydrological, and sociopolitical circumstances are used for site-specific safety assessments. There aren't many thorough studies that evaluate the economics of sophisticated RWM systems across various reactor types.
- How New Waste Forms Act Over Time: The mechanics of current immobilization materials' deterioration under repository conditions are not well documented. Few studies have been conducted on the waste volume and management implications of upcoming small modular reactors (SMRs).
- Lack of sustainability and regional regulatory harmonization.

This data has led to the formulation of the following question:
For nuclear power operations, including new reactor designs, how can site-specific and lifecycle-optimized radioactive waste management methods be created to increase safety, cost effectiveness, regulatory requirements and sustainability?

1. 2. Systematic Review Protocol

One of the biggest challenges facing the global nuclear industry is managing radioactive waste (RWM), especially with regard to nuclear power plants (NPPs). In order to find and examine current and new trends in RWM practices at NPPs, this study provides a thorough process for carrying out a systematic review. A study of this kind is crucial for directing research, influencing policy, and promoting the safe and sustainable use of nuclear technologies globally. To conduct a thorough, expert-level literature study on Trends in Radioactive Waste Management at Nuclear Power Plants, a methodical, multi-layered strategy combining scientific rigor, technological insight, and regulatory awareness is needed.
A systematic review offers an organized, open, and repeatable process for finding, assessing, and combining all pertinent data on a given subject. By reducing prejudice and avoiding unintentional duplication of research efforts, this rigorous approach helps to maximize research resources. A systematic study enables a thorough and objective synthesis of global knowledge and experience because of the intrinsic complexity and multifaceted character of RWM, which encompasses technical, regulatory, economic, and sociological aspects. This approach guarantees that any trends observed are supported by a careful and rigorous analysis of the body of existing literature, offering a strong basis for further study, the

creation of policies, and real-world application in the area.

From the literature search to the data synthesis, the entire systematic review process is guided by the study question's clarity and accuracy. The main question is defined in this part, together with important supporting questions, to guarantee a thorough investigation of the "trends" component of radioactive waste management at NPPs. "What are the current and emerging trends in radioactive waste management practices at Nuclear Power Plants globally?" is the main research question that drives this systematic study.

The scope of this subject is sufficiently broad to cover the several aspects of "trends," such as methodological developments, economic considerations, regulatory changes, public perspectives, and technological improvements. While "globally" guarantees an international perspective and is in line with the extensive international collaboration and data collection efforts of organizations like the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (NEA), the inclusion of "current and emerging" focuses attention on recent developments and future directions.

Inclusion and Exclusion Criteria

The following criteria have been chosen for inclusion and exclusion:

- **Inclusion**:
  - Peer-reviewed journal articles
  - Conference proceedings
  - IAEA/NEA/US NRC/EC/EPRI/DOE reports
  - Publications from 2000 to 2025
  - English-language sources
- **Exclusion**:
  - Non-nuclear waste management
  - Non-peer-reviewed or unpublished reports
  - Duplicate or regionally irrelevant studies

Select Databases and Search Engines

The following reputable sources have been used:

- Scopus
- Web of Science
- ScienceDirect
- PubMed (for environmental/health impacts)
- Google Scholar
- IAEA Publications & INIS

Search Strategy

The Boolean keyword strings listed below have been utilized:

("radioactive waste" OR "nuclear waste") AND ("management" OR "treatment" OR "disposal") AND ("nuclear power plant" OR "NPP") AND ("trends" OR "review" OR "technologies" OR "regulations")

Fig. 1 shows a notional flow diagram for the review procedure.

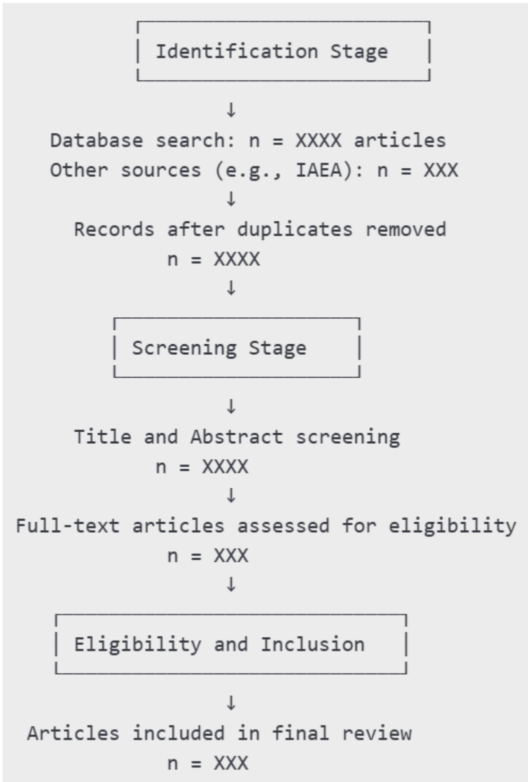

Fig. 1. Flow Diagram (PRISMA-style) for the review search procedure.

Figure 2 displays the publishing trends over time for the search data.

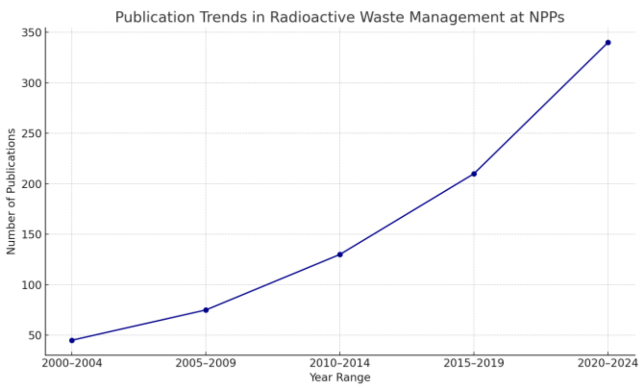

Fig. 2. Number of publications related to radioactive waste management at NPPs over the years.

2 Types of Radioactive Waste

Due to the high risk of nuclear waste, it is essential to effectively manage the entire process of radioactive waste, minimizing the harm done to the environment and people by its radioactivity. The study of nuclear waste management therefore has significant theoretical and practical implications.The classification of some commodities as radioactive waste, such as used nuclear fuel and plutonium, is determined by government policy. From the point of origin to collection, isolation, treatment, conditioning, storage, transportation, and final disposal, radioactive waste is classified according to each stage [12-15]. Fig. 3 depicts the general classification of radioactive waste according to life span and kind.The next part provides a quick explanation of Fig. 3 [15].

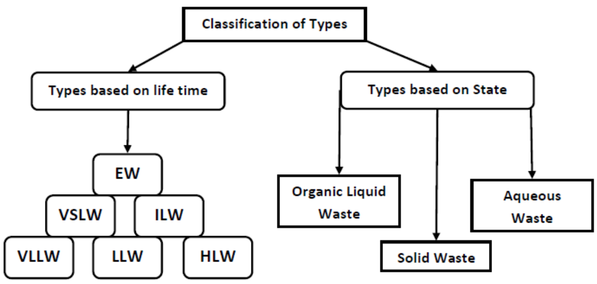

Fig. 3. Basic classification of nuclear waste (author's own creation).

2.1 Exempt waste (EW)

It is a radioactive waste with low radioactivity content and a short lifespan. It doesn't require management in the same way as other wastes.

2.2 Very short-lived waste (VSLW)

Radioactive waste that can only be kept for a short time, perhaps a few years, in order for the radioactivity to degrade. Despite its brief duration, this class contains highly radioactive material. The majority of the wastes are main radionuclides that are utilized in research and medicine.

2.3 Very low-level waste (VLLW)

Very low-level waste (VLLW) and exempt waste both contain radioactive substances, but at levels deemed safe for people and the environment. It is acceptable to dispose of them in the ground or in landfills because their radioactivity is equivalent to that of natural radioactivity.

2.4 Intermediate-Level Waste (ILW)

High levels of radioactivity and the majority of a reactor's main core components can be found in ILW. Ion exchange resins, chemical sludge, metal fuel cladding, and contaminated substances from reactor operation are common components of ILW.It contains a high concentration of radioactivity and a long life of hundreds of years. Therefore, it is important to manage intermediate-level waste (ILW) carefully.Long-lived radionuclides, in particular α-emitting elements, may be present in ILW. Such radionuclides need a lot of time to decay without reaching a high level of activity concentration. Compared to low-level waste, it is more radioactive and needs to be handled with proper shielding.Despite being more radioactive than LLW, ILW produces too little heat (2 kW/m^3) to be taken into consideration when developing or picking interim storage and final disposal facilities. Due to its greater radiation levels, ILW requires some form of protection [2, 15].

2.5 Low-level radioactive waste (LLW)

The categories of intermediate-level or high-level radioactive waste do not apply to LLW. It is free of potentially harmful radiation and could be a collection of LLW with a low amount of radioactivity. These wastes are created when items are exposed to radiation or get contaminated with it. Such wastes can be handled with little particular protection and are simple to dispose of in compacted form. LLW does not require radiation shielding when being handled or transported, and it can be disposed of in places that are close to the surface. Work clothing, gloves, paper, enriched liquid waste, and other materials used in plant operation and maintenance make up the majority of low-level radioactive waste from NPPs. They are either burned, compacted, or cemented with cement and asphalt before being placed in metal drums to minimize their volume. Such waste can be disposed of in specially designed facilities near the surface, but it needs to be strongly separated and contained for up to a few hundred years.Non-combustible solid wastes are combined with concrete, drummed, and sent for burial beneath deep earth, whereas combustible solid wastes are burned. Long-lived radionuclides and short-lived radioactive substances may both be present in LLW at higher activity concentration levels. Short-lived isotopes in a given stream of radioactive liquid waste may be held for a long enough time to assure that the majority of radionuclides decay, thus adhering to the "delay and decay" principles [15].

2.6 High-level radioactive waste (HLW)

High level radioactive waste is defined as waste that contains much more short- and long-lived radioactive materials than ILW and hence requires a higher level of shielded containment and isolation from the accessible natural environment in order to ensure long-term protection. Such shielded containment and isolation is often ensured by man made barriers as well as the stability and integrity of deep geological disposal systems. Due to radioactive decay, HLW produces a considerable amount of heat and typically keeps doing so for several millennia. HLW covers any waste needing an equivalent level of containment and isolation, including conditioned waste produced during the reprocessing of spent fuel. National nuclear regulatory authorities may determine that specific waste constitutes ILW or HLW for communication purposes while waiting for the construction of HLW disposal facilities based on general safety cases [15].

3 Radioactive Waste Lifecycle

Different types of radioactive waste are being created from nuclear power plant's operation, repair and maintenance, decommissioning, and spent fuel pools. The general scheme of waste production and process is briefly described in Fig. 4 [15].

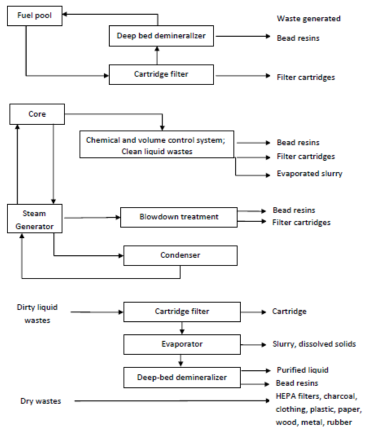

Fig. 4. Generic flow chart of the waste generation in a NPP (PWR)(author's own creation).

Fig. 5 [15] depicts the primary waste handling stages. Characterization of nuclear waste is crucial at every level of radioactive waste management and is required from the start of the nuclear waste life cycle. It entails figuring out the waste's physical, chemical, and radiological characteristics in order to determine if it needs additional adjusting, conditioning, or treatment—or whether it can be handled, processed, stored, or disposed of—or not. The pre-treatment stage's upfront characterisation is crucial for the technical decision-making process that involves picking the most effective treatment method. Pre-disposal and disposal stages are traditionally used to categorize operations related to radioactive waste [4]. Pre-disposal involves processing (such as pre-treatment, treatment, and conditioning), temporary (interim) storage, and transportation. It encompasses all the processes in the management of radioactive waste from its generation up to disposal. Waste is to be permanently disposed of by being placed in a suitable location without any plans to retrieve it. No phase should conflict with or compromise a future waste management step in order to fulfill the overall goal of safe radioactive waste management. Instead, component processes should be complementary and compatible with one another. Radioactive waste (radioactive material with qualities that make it inappropriate for allowed release, authorized usage, or clearance from regulatory supervision) is used by nuclear power plants and research reactors to generate electricity [16].

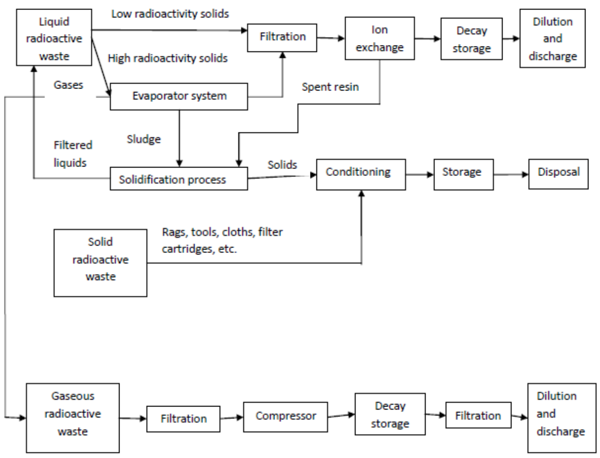

Fig. 5. Flow diagram for different steps of radioactive waste management systems ((author's own creation)).

After generation, the radioactive waste life cycle is conceptually broken down into the following stages [15]:

1. Pretreatment covers any actions taken before waste treatment in order to choose the technologies that will be employed later in the waste processing (treatment and conditioning) process.
2. The procedures designed to change the characteristics of radioactive waste in order to increase safety or reduce costs are included in the treatment of radioactive waste. Depending on the treatment, the waste may take the right form.
3. Conditioning entails procedures that result in a waste package that is appropriate for handling, transportation, storage, and/or disposal.
4. Radioactive waste storage entails keeping the waste in a way that guarantees its irretrievability and provides confinement, isolation, environmental protection, and monitoring during the storage term.
5. Disposal entails putting waste in a suitable facility without planning to retrieve it. Be aware that in some nations, controlled effluent discharge to the environment is frequently seen as a permitted disposal alternative.

According to their physical state, radioactive wastes can be efficiently classified into three generic groups:

- Solid radioactive waste (wet and dry),
- Liquid radioactive waste (aqueous and organic),
- Gaseous radioactive waste (including airborne effluents).

As briefly discussed below, additional categories that are connected to management steps may be used. The waste processing phases that are based on the processing technologies utilized are typically related to the waste categories [4, 15].

- Combustible waste, which includes paper, plastic, wood, and organic materials;
- non-combustible waste, which includes construction materials and bulk metallic items; compressible waste, which includes solid combustibles and light metals (such as aluminum); and
- non-compactable waste, which includes metals, concrete, and glass.

The process of treating primary or "raw" radioactive waste involves steps aimed at improving safety and efficiency by modifying the waste's nature.

- Volume reduction,
- Radionuclide removal, and
- Physical and chemical composition change are the three main treatment goals.

Before selecting a waste processing strategy, it is crucial to understand the radioactive waste source, pace of radioactive waste creation, amount of radioactivity, and characteristics of the waste. The appropriate safety requirements and potential waste processing options are determined using this information. Sorting and segregation to distinguish between contaminated and non-contaminated materials may be a part of pre-treatment, which gets trash ready for processing. It may occasionally be necessary to reduce the size of the trash by, for example, cutting or shredding it, in order to maximize its downstream processing. The trash is treated after being appropriately prepared in order to improve its safety and reduce the expenses of the next phases of management, such as storage or disposal.There are various waste treatment processing techniques that can be used, depending on the type of waste and the waste acceptance policies of the disposal site. Burning is normally used to treat solid trash, and evaporation is usually used to treat liquid waste.

Figure 6 demonstrates [15] how precast concrete boxes are used to fix and solidify garbage. Resins, sludge, activated equipment, and other materials all respond well to this technique. But compared to untreated trash, the approach considerably increases waste volume, by a factor of 4 to 40.

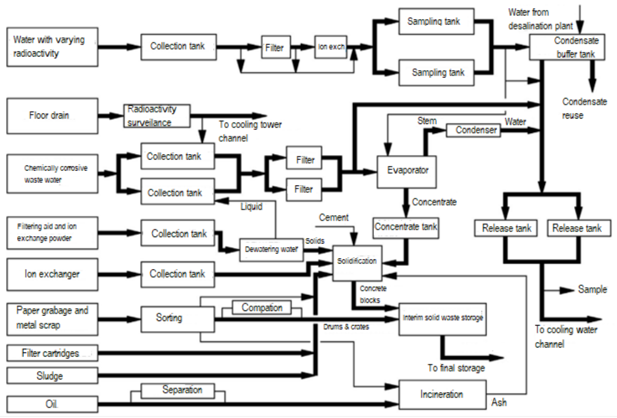

Fig. 6. There are various changes to the typical nuclear power plant waste management system (author's own creation).

The radioactive waste material generated by NPPs has a wide variety of radioactive elements, half-lives, activity concentrations, volumes, and physical and chemical properties. In general, spent ion exchange resins, filter papers, activated materials, liquid and gaseous effluents, radioactive experimental parts, and waste from decommissioning make up nuclear power plants' waste.All phases of the waste management process must be given special care over protracted periods of time due to the diversity and fluctuation in the waste streams from such facilities.At a centralized radioactive waste facility, various radioactive waste types take separate processing paths [17]. Figures 7 and 8 provide schematic representations of typical processing methods for liquid and solid radioactive wastes, respectively [15, 17]. Although there are many technological choices available, this graphic demonstrates one particular method of treating the many waste kinds.

4 Methodology

Provide sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference.Only relevant modifications should be described.

4.1 WASTE MANAGEMENT SAFETY PROCEDURES

Planning and preparation, treatment, packing, storage, and disposal are some of the processes involved in managing radioactive waste as per IAEA procedures [19-20].International legislative mechanisms like the Joint Convention on the Safety of Spent Fuel Management and on the Safety of

Radioactive Waste Management [21] have laid out similar safety considerations and requirements for excellent behavior.According to GSR Part 5 [20], the term "predisposal management of radioactive waste" refers to all procedures involved in managing radioactive waste, from its generation to (but excluding) its disposal, including waste processing, storage, and transport.

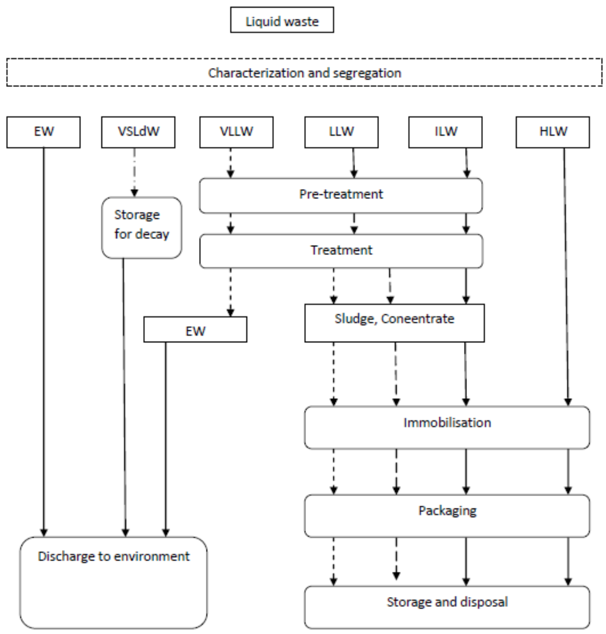

Fig. 7. Typical liquid radioactive waste management procedures(author’s own creation).

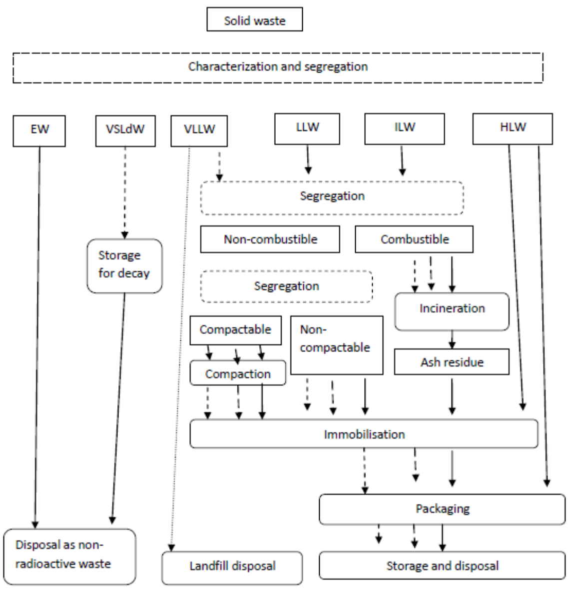

Fig. 8. Typical solid radioactive waste management procedures(author’s own creation).

Processing is needed to make nuclear waste safe for disposal. This entails gathering and sorting garbage, cutting down on its volume and changing its chemical and physical composition, such as by concentrating liquid waste, before conditioning it to immobilize and package it before being stored and disposed of.Characterization is a technique that provides information on the physical, chemical, and radiological traits of the waste. The appropriate safety requirements and potential processing options are determined using this data. It also ensures compatibility and conformance to accepted disposal and storage standards.To reduce disposal costs and the amount of waste that needs to be temporarily stored, all countries are taking or intend to take measures to reduce the volume of rubbish that arises. For low-level waste, which frequently has a big volume but low radiation activity, reduced volume is particularly appealing. Administrative adjustments, such as the use of durable, reusable protective gear, the use of hot air dryers in place of paper towels, etc., as well as general improvements to operational execution, or "housekeeping," can have a large positive impact.

4.2 PRACTICE TECHNOLOGIES

Many nations with limited nuclear programs lack the financial and personnel resources necessary to build and run a geological disposal site because not all nations have the ideal geological conditions for such disposal. There are currently three methods that are frequently used to store nuclear waste.After the fuel is burned, it is placed in water pools for 10 years to reduce radioactivity, then it is contained in dry storage casks for 50 years. The second alternative is to store it in permanent pools or dry casks. The second alternative is known as a "deep geological repository" and entails burrowing the garbage far underground for tens of thousands of years [22-25]. The majority of countries have struggled with this due to the significant investment and the local governments' and residents' opposition to having the site in their area. This is the safest method for the environment and humans, and it will primarily concern high and intermediate level waste. The general management procedure and methods of radioactive waste is shown in Figs. 9 and 10.

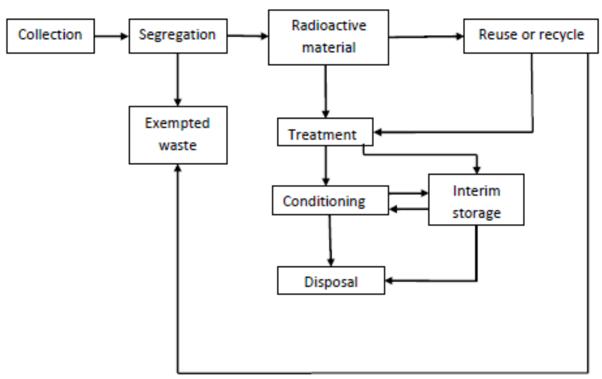

Fig. 9. Generic procedure for radioactive waste management(author’s own creation).

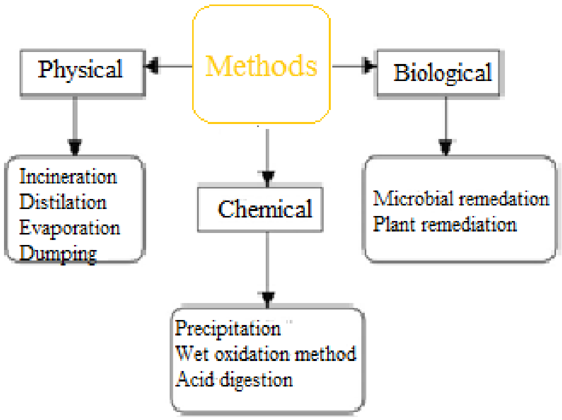

Fig. 10. Types of treatment methods(author's own creation).

Methods under consideration for management of nuclear waste are described briefly as follows:

Collection and segregation

The radioactive wastes produced in the NPP are collected in a container with proper identification. After collection of the radioactive wastes, wastes are segregated as peer standard procedures [15].At every stage of waste management, including the beginning of the radioactive waste life cycle, it is crucial to characterize radioactive waste. It entails determining the waste's physical, chemical, and radiological characteristics in order to determine whether it needs additional adjusting, conditioning, or treatment or whether it is suitable for additional handling, processing, storage, and disposal.

Compaction

Compaction is done to concentrate the radionuclides and reduce the volume of trash. With traditional compactors, plastics, paper, absorbent material, and cloth are all acceptable [16]. Super compactors can handle materials like wood, metal pipe, valves, conduit, and other similar materials.

Chemical precipitation

At fuel reprocessing facilities, research labs, and power plants, chemical precipitation procedures are frequently employed to remove radioactivity from low and intermediate level aqueous wastes [26-29]. Precipitation processes can handle a wide range of liquid effluents, from those with large volumes of particulates or high concentrations of inactive salts to those with relatively low concentrations of active species and relatively low investment and operating costs.

Ion exchange/sorption

Ion exchange techniques are widely used to remove soluble radionuclides from liquid waste generated in radioisotope production, nuclear fuel cycle operations, and research facilities [26]. The radioactive content of a big volume of liquid can be effectively transferred into a tiny volume of solid. The ion exchange process includes exchanging cations or anion between a liquid solution and an insoluble solid matrix that contains ionisable polar groups.

Evaporation

Salts, heavy metals, and other hazardous substances can be concentrated or removed from waste effluent using the evaporation method, which also reduces huge volumes of liquid wastes with high factor decontaminations [15]. The procedure is frequently used to treat high-, intermediate-, and low-level waste effluents; in particular, it is utilized to treat small volumes of highly active effluents. It can be completed using evaporation equipment that is readily available on the market.

Transmutation

Long-term disposal is also possible through transmutation. It entails specifically converting one chemical element into a less hazardous one. Geological storage is also motivated by natural transmutation since it is believed that, given enough time in isolation, the waste will change into a substance that is neither toxic nor fissionable [30-32].

Ocean-dumping

The world's industrialized nations view the disposal of waste on the ocean floor as the least expensive option [33-36]. They had to oversee this plan for a long time. The USA, France, Great Britain, and Russia are a few of the nations that fall under this management group. Before the US Senate passed a law banning the disposal of radioactive waste in the water in 1982, the US dumped an estimated 112,000 drums at 30 separate locations in the Atlantic and Pacific oceans. Even though the majority of nations with nuclear programs have outlawed this behavior, the issue still exists. Russia continues to dump its nuclear waste into the oceans despite controlling 60% of the world's nuclear reactors.

Geological Disposal

The process of managing radioactive waste ends with disposal [37-40]. It entails storing radioactive waste in a repository or other site to protect it from accidental disruption and to prevent any waste material from escaping for a lengthy period of time. Disposal may also involve the release of effluents into the environment with subsequent dispersion, such as the sea, rivers, natural water basins, and atmosphere. This is always carried out under extremely strict, pre-approved boundaries.The fundamental concern with any disposal option is safety, which is mostly achieved via containment and concentration, which include isolating radioactive waste that has been properly conditioned in a disposal facility. To prevent radionuclides from dispersing into the environment, containment uses a variety of barriers to enclose radioactive waste. The limiting boundaries may be created artificially or naturally. Typically, a containment system consists of several barriers.

Seduction method

One tectonic plate moves under another during the process of seduction, eventually being reabsorbed into the mantle. In order to transport the trash beneath the Earth's crust, where it will be diluted and spread across the mantle, the seductive waste disposal method creates a high-level radioactive waste deposit in a subducting plate [89]. The most advanced technique for disposing of nuclear waste is this one. It is the only practical method of getting rid of radioactive waste that guarantees that the substance is not returned to the biosphere.

4.3 New Developments

The majority of LILW treatment and conditioning procedures have now developed to a sophisticated industrial scale.Although these procedures and technologies are adequate for managing radioactive waste at nuclear power plants, it is still feasible and desirable to make more advancement in this field. The rising expense of disposing of radioactive waste encourages the adoption of methods and tactics that reduce radioactive waste production, as well as the creation of new methods that reduce volumes at the treatment and conditioning stage. It is not possible to list all recent advancements and improvements being made in this direction in different countries at this time.The majority of LILW treatment and conditioning procedures have now developed to a sophisticated industrial scale.The use of specific inorganic sorbents to enhance the treatment of liquid waste, the use of membrane techniques for the treatment of liquid waste, the dewatering and drying of bead resin and filter slurries, the incineration of used ion-exchange resins, the dry cleaning of protective clothing to reduce the amount of laundry drains, the use of high integrity containers for packaged dried filter sludge, and the vitrification of some intermediate-level waste to lessen pollution are some examples.Especially in nuclear power plants, not all of these recent improvements in waste management systems will likely be broadly embraced. Although advancements in current technology are anticipated, research and development shows that the nuclear industry and utilities take great care to manage radioactive waste at nuclear power plants in a safe and cost-effective manner [41].

Immobilization/Vitrification

Cementation, bituminization, and vitrification are the three basic immobilization techniques that are commercially accessible and have been shown to be effective. Vitrification achieves the maximum level of volume reduction and safety, but it is also the most difficult and expensive process, requiring a hefty initial capital outlay. Although they have limits, as was previously mentioned, these immobilizing technologies provide a reasonable level of safety. Furthermore, it is known that there are challenging legacy waste streams for which the available technology is insufficient, necessitating the development of new strategies.Waste pollutants are incorporated into the final vitreous product's macro- and microstructure through the process of vitrification, which involves melting waste materials with glass-forming chemicals. The material of choice for immobilizing both high-level and low-level waste (HLW and LILW) worldwide is borosilicate glass [42] Polymeric materials have been utilized to immobilize radioactive waste because they have a high radionuclide retention rate and get along well with other waste products, like old IEX resins [43]. Epoxy resins, polyesters, and styrene are the most common polymeric compounds in use. IEX and other radioactive waste are often dried, combined with liquid polymeric material, and then allowed to solidify with the use of additives like epoxy resin hardeners or temperature-lowering polyethylene.

Synroc

To address some of the problematic residual wastes, new non-thermal and thermal approaches are being explored. Single-phase minerals can serve as a monophasic waste form and can contain a variety of nuclides. Polyphase compositions are more typical, and monophase ceramics are more difficult to manufacture. To obtain complete and dependable immobilization of the waste constituents, the composition of the polyphase ceramic is matched to that of the waste composition.Synroc is the most well-known polyphase ceramic for the immobilization of nuclear waste. Short for "Synthetic Rock," T. Ringwood of the Australian National University created the term in 1978. Natural titanate minerals that have been immobilizing uranium and thorium for billions of years are the basis for Synroc. These minerals are geochemically stable. The Australian Synroc (synthetic rock) is a more sophisticated means of immobilizing such garbage, and this process may one day be utilized commercially for civil wastes (it is now being developed for U.S. military wastes). At ANSTO, work on a Synroc waste treatment facility started in 2018 [44-46].

Accelerator Driven System (ADS)

Partitioning and transmutation methods seek to ease the burden on the geological storage system by reducing the mass of the nuclear waste, lowering the heat load, and ultimately lowering the quantity of potentially radiotoxic isotopes by using ADS. Transmutation studies aim to recycle radiotoxic long-lived elements found in waste into non-radioactive or shorter-lived elements. These elements include the minor actinides (MAs) americium, curium, and neptunium. Nuclear transmutation refers to the conversion of one chemical element or isotope into another chemical element. Nuclear transmutation is the term for any process that alters the number of protons or neutrons in an atom's nucleus. There have been suggestions for reactors that consume nuclear waste and change it into alternative, less harmful, or temporary nuclear waste. Another approach, regarded to be safer but requiring more study and development, is to use subcritical reactors to transmute the remaining transuranic elements [30-32].

Biological Methods

Recent advances in bioscience have had a profound impact on research outcomes, not just in biology but also in interdisciplinary fields like electrochemistry, biotechnology, and bioinformatics, among others. According to Varagunapandiyanet al. [47], biological techniques are essential for the environmentally acceptable handling of radioactive waste. Even if they can't change the waste into a less radioactive or nonradioactive state, physical and chemical procedures are expensive and require a lot of care. The utilization of radionuclides for growth and the potential conversion of radioactive waste into nonradioactive form are both possible using biological processes. Microbial remediation, plant remediation, phytoremediation, etc. are a few examples of biological techniques [47-50].Bioremediation is a method for disposing of radioactive waste and turning it into electricity that is based on technological advancement and knowledge of bacteria. Microbes and plants are currently and maybe in the near future playing an important part in the management of radioactive waste. When compared to bioremediation and plant remediation, the main approaches in the literature are expensive and difficult to maintain. The plants and bacteria used are practical, affordable, and environmentally beneficial [48-53].

5. Recent Technologies for Radioactive Waste Treatment and Management at NPPs

Nuclear power generation relies heavily on the management of radioactive waste, which calls for constant improvements in disposal and treatment technology. Recent advancements have concentrated on improving the sustainability, efficiency, and safety of managing different types of radioactive waste. One essential component of nuclear power generating is the management of radioactive waste, which calls for constant improvements in disposal and treatment technology. In processing different types of radioactive waste, recent advancements have concentrated on improving sustainability, efficiency, and safety [55-59].

1. Transmutation of nuclear waste

Switzerland has approved nuclear transmutation technology, which transforms long-lived radioactive isotopes into stable or shorter-lived ones using particle accelerators. This strategy presents a viable answer to long-term storage issues by potentially reducing the amount of high-level radioactive waste by up to 80% and bringing its hazardous lifespan down to less than 500 years.

2. Deep Geological Repositories (DGRs)

With its Onkalo facility, Finland is leading the way in the deployment of deep geological repositories that can safely store spent nuclear material for up to 100,000 years. To stop radioactive movement, the repository uses a variety of barrier technologies, such as bentonite clay and copper canisters.

3. Systems for Treating Hybrid Liquid Waste

Developments in the treatment of radioactive liquid waste have resulted in the creation of hybrid systems that combine membrane filtration and adsorption methods. These systems have proven to be highly effective in eliminating radionuclides like strontium-90 and cesium-137, which could lead to resource recovery and safer wastewater treatment.

4. Technologies for Photonuclear Treatment

The transformation of minor actinides found in spent nuclear fuel is being investigated using new photonuclear techniques. As an alternative to conventional neutron-based transmutation procedures, this technology uses high-energy photons to lessen the radiotoxicity and heat load of nuclear waste.

5. Digital Imaging Enhanced by AI for Waste Characterization

The characterization of radioactive waste has been enhanced by the combination of artificial intelligence with Compton imaging technologies. These cutting-edge imaging methods improve safety and efficiency during decommissioning operations by enabling the real-time visualization and identification of radioactive elements.

6. SCWO, or supercritical water oxidation
For the treatment of organic radioactive waste, SCWO technology is becoming more popular. This technique, which works at supercritical circumstances, efficiently oxidizes organic compounds, reducing waste volume and destroying dangerous components, making it an environmentally benign waste management choice.

7. Synroc Waste Immobilization Technology
By integrating radioactive waste into a solid ceramic matrix, Synroc (synthetic rock) technology imitates the structures of real minerals. By improving the immobilization of high-level waste, this technique lowers the possibility of radioactive leaking and makes long-term storage safer.

8. AI and Robotics in Waste Management
With research institutes like the UK's National Centre for Nuclear robots creating autonomous systems for waste processing and decommissioning operations, the use of robots and artificial intelligence in nuclear waste management is progressing. The goals of these devices are to increase operational effectiveness and reduce human exposure.

These developments in technology mark important progress in tackling the intricate problems associated with managing radioactive waste in the nuclear power sector. To ensure the safe, effective, and sustainable handling of radioactive materials, more research and development in these areas is necessary.

6. Interdisciplinary combination of systems for waste management

An interdisciplinary combination of systems engineering, environmental modeling, regulatory foresight, and socio-technical optimization is needed to develop site-specific and lifecycle-optimized radioactive waste management strategies for nuclear power operations, including new reactor designs like SMRs, Gen IV, or advanced VVERs. The following is an expert-level analysis organized according to four main goals: sustainability, cost-effectiveness, safety, and regulatory compliance [54-59].

6.1. Design for Waste Management Driven by Safety

a. Early-Stage Integration of Design
Through actinide recycling, low-activation structural materials, and modular fuel assemblies that provide simpler post-irradiation handling, waste minimization must be ingrained in reactor design. In-situ transmutation of long-lived isotopes can be made possible by advanced designs such as MSRs or fast reactors, which lowers the quantities of high-level waste (HLW).
b. Engineered Barriers with Risk-informed Siting
Permeability, seismicity, hydrology, and other site-specific geotechnical evaluations establish the ideal depth and arrangement for near-surface, intermediate-deep, or geological repositories. Use materials science (e.g., bentonite, borosilicate glass, corrosion-resistant alloys) to create site-specific multi-barrier isolation systems, both natural and manmade.

6.2. Dynamic Inventory Modeling for Lifecycle Optimization

a. Utilize ORIGEN, SCALE, or OpenMC to model isotopic inventory under off-normal circumstances and during reactor cycles. To facilitate in-the-moment decision-making, combine this with a digital simulation of the waste stream. Build the backend fuel cycle as a modular system with buffer decay stages, monitored retrievable storage (MRS) to postpone final disposal, and segmented storage (wet-to-dry).
b. Classification and Segregation of Waste
Nuclide-specific decay heat, radiotoxicity, and neutron emission metrics are used to create material-specific routes (LLW, ILW, HLW, and TRU). Promote volume reduction techniques such as supercompaction, vitrification, and plasma arc treatment on-site, particularly in settings with limited infrastructure or distant locations.

6.3. Cost-effectiveness Using Adaptive and Modular Systems

a. Modules and Standardization
Regulatory approval is made easier and disposal costs are reduced per unit when modular encapsulation and cask systems (such as Holtec HI-STORM and GNS CASTOR) are standardized across locations. Use pooled regional interim storage facilities or transportable dry storage to cut expenses for nations with smaller reactor fleets.
b.Scope Economies
Work together to share infrastructure for treatment, storage, and transportation with medicinal isotope and decommissioning initiatives. In order to treat spent fuel and legacy trash alongside reprocessing or MOX manufacture, multipurpose facilities should be pursued.

6.4. Regulatory Needs and Flexible Licensing

a. Performance-Based Licensing

Instead of adopting prescriptive regulations, use performance objectives to align with IAEA GSR Part 5 and national standards. For long-term storage facilities, use adaptive licensing and periodic safety reassessment (PSR) in accordance with improvements in climate resilience and technology.
b. Digital Tools for Compliance
Utilize smart contracts or blockchain technology to track radioactive waste, improving stakeholder confidence, transparency, and regulatory auditability. Incorporate AI-powered decision support tools for scenario modeling while adhering to legal restrictions (such as canister corrosion rates and thermal loading).

6.5. Integration of Sustainability and the Economy

a Valorization of Waste and Recovery of Resources
Retrieve valuable elements from HLW and fuel cladding, such as rare earths and platinum group metals from fission products. Reduce the HLW burden in Gen IV rapid spectrum systems by implementing partitioning and transmutation (P&T) techniques.
a. Involvement of Stakeholders and Ethical Management
Create community-based consent models that prioritize openness and intergenerational equity and have a long-term social license. Plan for knowledge preservation (institutional memory frameworks, digital repositories) to guarantee long-term supervision after institutional lifetimes.

A site-specific, lifecycle-managed, and optimized radioactive waste system must handle radioactive materials as a dynamic, resource-sensitive, and socially integrated system rather than just as liabilities. The long-term viability of modern nuclear power programs can be supported by nuclear waste management that integrates safety, economy, regulatory agility, and sustainability into every stage—from design to disposal.

Table 1: Best Practices in Action: Some Case Studies.

Reactor Type	Waste management strategy	Remarks and best practices
PWR (e.g., U.S., France, China	Spent fuel initially cooled in pool storage, followed by dual-purpose dry cask systems (e.g., HI-STORM, TN-24). Reprocessing in France (La Hague), closed cycle in China.	High burnup fuels and zirconium-based cladding increase decay heat and storage time. U.S. relies on interim storage; no final repository operational yet.
BWR (e.g., Japan, Sweden, U.S.)	Similar to PWRs but with higher water content in spent fuel and more neutron activation products. Dry casks used after ~10 years of pool storage. Sweden uses KBS-3 copper/canister-based deep geological disposal.	Japan and Finland use on-site interim facilities, while Sweden leads with a deep repository under construction.
VVER-1200 (Rooppur, Bangladesh	Uses Russian-designed transport/storage casks (TK-6, CONSTOR), often returns spent fuel to Russia under bilateral agreements. Long-term closed cycle policy in Russia; Bangladesh developing a repository.	Incorporates Russian-style dry cask systems and interim storage. Significant international collaboration; potential use of Russian Federation's central storage.
SMRs (e.g., NuScale, CAREM, RITM-200)	On-site integrated storage, modular waste logistics Smaller, modular waste volume; often stored on-site for entire operating life. Integrated fuel cycle contracts possible with vendor nations (e.g., Russia, U.S.).	Small waste footprint supports centralized backend design Potential for transportable fuel-return models. Ideal for countries without national repository infrastructure.
BN-800 Fast Reactor	Reuse of plutonium/MOX, P&T strategy	Supports closed fuel cycle goals and HLW minimization
Canadian CANDU	Use of existing dry storage modules, potential for DUPIC fuel cycle Uses dry storage canisters (MACSTOR, CANSTOR) almost immediately due to low burnup. Canadian NWMO planning a Deep Geological Repository (DGR).	Reduces uranium demand, repurposes spent PWR fuel. Can exploit DUPIC cycle (direct use of spent PWR fuel), offering synergy between PWR/CANDU countries.

Many nations have used various waste management strategies; for instance, Table 1 highlights a few case studies, including Bangladesh. By 2026/2027, two VVER-1200 nuclear power reactors will be operational at the Rooppur site in Bangladesh. In order to accomplish the Sustainable Development Goals (SDGs) for lowering greenhouse gas emissions and ensuring safe waste management that does not burden future generations, this study will assist operators, policy makers, and regulators in developing long-term, cost-effective waste management systems. Within the framework of the VVER-1200 reactor, which uses fuel assemblies manufactured in Russia (TVS-2M or TVS-4), the infrastructure for transporting spent fuel and storing it dry is closely linked to the Russian fuel cycle plan. In Russia, this covers both on-site temporary storage and, if relevant, fuel return contracts for reprocessing or ultimate disposal. Table 2 illustrates the suggested work strategy for VVER-1200 programs at the Rooppur location.

Table 2: Recommended Cask Strategy for VVER-1200 Programs.

Application	Recommended Cask	Justification
Short-term storage (on-site)	Spent Fuel Pool (SFP), CONSTOR® V	Proven system, radiological buffer
Mid-term (dry storage)	CONSTOR® V/TC or V/MB series	High capacity, modularity, passive cooling
Transport to Russia or repository	TK-6 or TUK-1410 Or locally fabricated dry storage cask that has regulatory authority approval.	IAEA compliant, shielded for high-burnup fuel
Future repository interface	Dual-purpose or disposal-ready canister	Long-term integration with back-end policy

7 Conclusions

Various types of nuclear waste are created during the operation, maintenance, and dismantling of NPPs. Due to the global expansion of nuclear reactors, there is now a major increase in the creation of radioactive waste. Radioactive waste needs to be identified, categorized, stored, transported, and disposed of carefully. Nuclear energy presents a problem in the management and process of radioactive waste, pollutants, and effluent since it poses a greater risk to all living things.At both the international and national levels, rules and regulations have been formed that give clear recommendations for radiation safety and the handling of radioactive waste. Different safety precautions and management plans should be used for different levels of nuclear waste. Finding a suitable location for the long-term disposal of nuclear waste is seen as a challenging task. Nearly all industrialized nations have experienced difficulties, and they are still concentrating on research to find the best adaptable answer.

Due to the extensive contamination that resulted from the last 70 years of nuclear activity, it is imperative to preserve and manage the disposal of radioactive waste by using physical, chemical, and biological means.Thus, it is essential to conduct research to advance all of these techniques in order to guarantee several long-term benefits. Process(es) chosen depend on the level of activity and the type (classification) of waste. The national laws and nuclear waste management regulations of each country also have an impact on the plan. By using conditioning methods like cementation and vitrification, waste is transformed into a solid, stable state that is insoluble and prevents dispersion to the surrounding environment. Adding the specified waste to the crystal structure of naturally occurring, geochemically stable minerals is a sophisticated tactic. It is essential to reduce the radioactivity of high level waste, which can be accomplished through nuclear transmutation. Bioremediation may be the most effective method for treating radioactive waste.Nuclear energy has always been regarded as the purest form of energy. It is crucial to the creation of energy everywhere in the world. It will be the most significant and significant source of energy production in the future. The only drawback is how its trash is handled or disposed of. We are aware that both physical and chemical procedures are used to dispose of the waste. Ongoing research and development in the field of managing radioactive waste has resulted in the creation of innovative techniques and technologies.The cutting-edge approaches emphasize reducing waste volume, isolating waste, cutting back on radioactive releases, and recovering usable materials from waste. Such advancements can give nations the tools they need to successfully manage initiatives involving radioactive waste.The outlook for the implementation of safe repositories for LLW, ILW, and HLW worldwide during the next few decades is positive in light of the numerous national initiatives, their promising progress, and international cooperation with regard to the final disposal of radioactive waste. In conclusion, by carefully adhering to the standards and rules of radioactive waste management, the general population and the environment will be protected by irradiation from the harmful radioactive waste.

All stages of the nuclear fuel cycle (NFC) generate some radioactive waste materials, and the expense of treating and managing of this waste is included in the cost of energy. All hazardous waste, not just radioactive waste must be managed safely because it makes up a relatively small portion of the total industrial toxic waste produced in countries that use NPP.

The sustainability of nuclear power and public confidence are still largely dependent on the handling of radioactive waste. Even though there have been notable advancements in waste reduction, conditioning, and storage, ongoing issues-particularly with regard to the disposal of HLW and the integration of new reactor types—require ongoing innovation and policy development. It will be essential to close research gaps through multidisciplinary studies and international collaboration in order to guarantee environmental preservation and long-term safety. The handling of radioactive waste is still essential to the development of sustainable nuclear power. The methods for classifying, processing, and disposing of radioactive waste have been described in this chapter, along with new developments that may influence future procedures. Particularly for high-activity and long-lived isotopes, the incorporation of vitrification, Synroc, and bioremediation into current waste protocols offers encouraging avenues for safer, more effective disposal. However, in addition to technology innovation, strong legislative frameworks, public involvement, and international cooperation are all necessary for successful implementation. To guarantee that radioactive waste management supports a safe and sustainable energy future, the nuclear industry must take a comprehensive approach going forward, striking a balance between technological competence, cost, and environmental responsibility.

8 Limitations

This study does not include empirical data or case studies from nuclear power plants; instead, it is based mostly on the body of current literature and IAEA guidelines. As a result, neither modeling nor field testing have confirmed the relative efficacy of new technologies like Synroc or biological remediation. Furthermore, even though the evaluation covers a wide range of waste treatment techniques, it omits lifetime and economic cost studies, which are crucial for real-world application, particularly in environments with restricted resources.

9 Future Research Directions

Future studies should concentrate on the following areas to solve the changing issues of managing radioactive waste:

-Quantitative evaluations contrasting the long-term safety, scalability, and cost of biological versus chemical waste treatment.

-Pilot-scale implementation of Synroc and vitrification methods for high-level waste in developing nuclear nations.

-Alignment of the regulatory framework for cross-border waste disposal and geological repositories in international collaboration.

-Monitoring and predictive management of waste processing and storage facilities through the use of AI and sensor networks.

-Techniques for public outreach to increase community support for long-term trash storage initiatives.

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