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Recycling the Irreversible: Chemical and Sustainable Approaches for Biomedical Waste Transformation

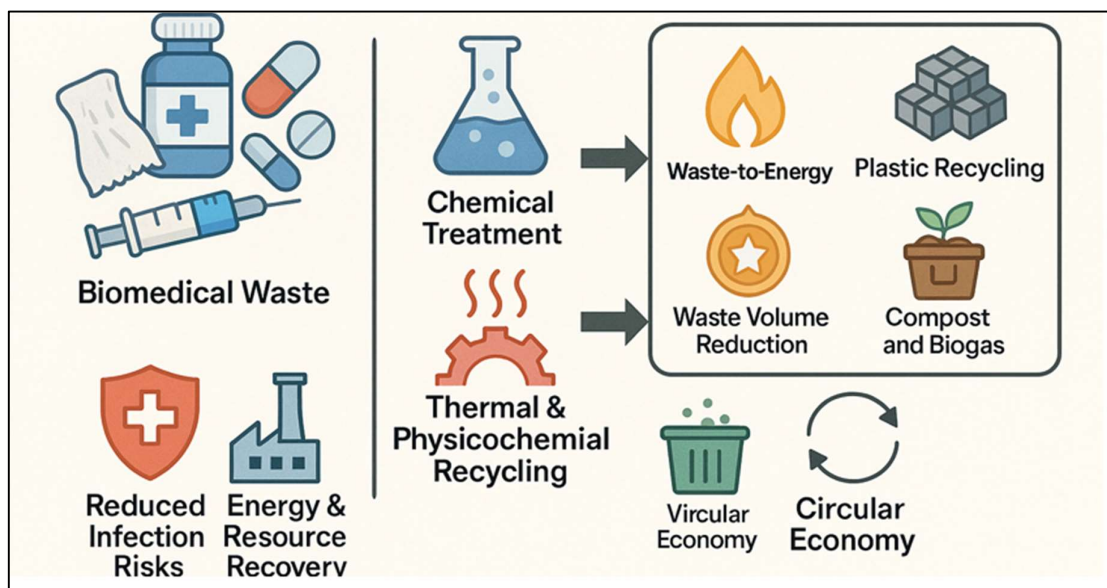
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Graphical Abstract

ABSTRACT

Biomedical waste represents one of the fastest-growing environmental challenges of the 21st century, exacerbated by rising healthcare demand and crises such as the COVID-19 pandemic. Traditional management strategies, including incineration, autoclaving, and deep burial, though effective in pathogen inactivation, are increasingly criticized for their environmental footprint, high operational costs, and risk of secondary pollution. To address these concerns, advanced treatments integrating chemical, thermal, and physicochemical approaches are being actively explored. Chemical methods such as disinfection, alkaline hydrolysis, solvent-based recovery, catalytic depolymerization, and plasma pyrolysis provide targeted solutions for sterilization and material recovery. Similarly, thermal and physicochemical recycling technologies—including microwave irradiation, pyrolysis, gasification, supercritical water oxidation, and photocatalysis—enable both energy generation and detoxification of complex biomedical residues. These innovations align with the principles of the circular economy, promoting waste-to-energy conversion, plastic-to-resin recycling, recovery of precious metals,



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and valorisation of organic fractions into compost and biogas. Collectively, these strategies not only reduce

1. Introduction

Healthcare systems are indispensable for safeguarding human life, but their benefits come with an often-overlooked cost—an immense burden of biomedical waste. This category of waste, generated during diagnosis, treatment, research, and immunization, includes items as varied as syringes, surgical dressings, pharmaceuticals, plastics, solvents, and sharps. The World Health Organisation (WHO) estimates that healthcare activities generate millions of tonnes of waste annually, of which approximately 15–20% is hazardous, posing risks of infection, toxicity, or radioactivity [1]. The sheer scale is alarming: for example, Tehran alone generates nearly 56,000 kilograms of medical waste daily, and similar patterns are evident across megacities in South Asia, Africa, and Latin America, where infrastructure has not kept pace with the expansion of healthcare [2].

Biomedical waste poses a dual threat, as it endangers both public health and the environment if not properly managed. Improper disposal has been linked to the spread of nosocomial infections, increased incidence of antimicrobial resistance, and heightened risks of long-term health effects such as cancers and reproductive disorders [3]. Communities living near poorly managed landfills or incinerators are especially vulnerable, as are waste workers and informal recyclers who handle discarded materials without protection. Studies indicate that exposure to biomedical waste can significantly raise the risk of respiratory diseases, congenital abnormalities, and infectious outbreaks, thereby extending the problem far beyond the boundaries of hospitals [4,5].

For decades, incineration and landfilling have been the main strategies to manage biomedical waste. While incineration ensures rapid volume reduction and pathogen destruction, it is also a pollution-intensive process. Emissions of dioxins, furans, heavy metals, and acidic gases contaminate air, soil, and water, creating long-lasting health hazards [6]. Epidemiological evidence links communities living near incineration plants to higher cancer risks, reproductive health issues, and infant mortality [7]. On the other hand, landfilling, the most common method in low- and middle-income countries, is often carried out in non-engineered sites where toxic leachates seep into groundwater and methane emissions exacerbate climate change [8]. These challenges highlight the unsustainability of linear “use-and-dispose” practices.

Against this backdrop, the concept of “Recycling the Irreversible” offers a transformative perspective. Instead of viewing biomedical waste as an unavoidable liability, it reframes it as a potential resource for recovery and reuse. Through chemical treatments (such as alkaline hydrolysis, catalytic depolymerization, and solvent recovery), thermal methods (like pyrolysis, gasification, and microwave irradiation), and physicochemical innovations (including supercritical water oxidation and photocatalysis), hazardous waste can be converted into fuels, reusable plastics, fertilisers, and even recovered metals [9,10]. This paradigm aligns with the circular economy model, ensuring that healthcare does not simply consume resources and generate waste, but contributes back to a regenerative system [11].



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This review explores the global challenge of biomedical waste, critically examining traditional disposal methods and their limitations while highlighting innovative chemical, thermal, and physicochemical approaches that convert waste into valuable resources. It aims to position biomedical waste not as an irreversible hazard but as a sustainable resource stream, aligning with circular economy principles and future healthcare innovation.

2. Types and Composition of Biomedical Waste

Biomedical waste is a highly diverse stream of discards, and its composition depends on the size, specialisation, and local practices of the hospital. Broadly, it can be divided into infectious waste, pharmaceutical and chemical waste, plastic waste, radioactive and hazardous fractions, and general healthcare discards. Each category carries unique risks and therefore requires specific management strategies.

Infectious Waste

The most recognised component of biomedical waste is infectious material, which includes used sharps such as needles, scalpels, lancets, along with blood-soaked dressings, swabs, and microbiological cultures. These materials are considered high-risk because they are capable of transmitting pathogens, including HIV, hepatitis B (HBV), and hepatitis C (HCV), when handled without adequate precautions. Studies show that improper disposal of sharps contributes significantly to accidental needle-stick injuries, which remain a persistent occupational hazard in hospitals [12].

Pharmaceutical and Chemical Waste

Another important fraction comprises expired or unused medicines, diagnostic reagents, disinfectants, solvents, and cytotoxic drugs. Cytotoxic agents used in

oncology are particularly concerning due to their mutagenic and carcinogenic properties, making the safe destruction of these agents essential [13]. The careless disposal of antibiotics and hormonal preparations into drains has been linked to antimicrobial resistance and endocrine disruption in aquatic life [14]. Similarly, solvents and reagents from diagnostic laboratories, if not neutralised, contribute to toxic leachates and chemical burns among handlers [15].

Plastic Waste

The largest single category of hospital waste by volume is plastics, making up nearly one-third of total biomedical waste. This includes disposable syringes, IV sets, gloves, masks, gowns, and PPE kits, primarily manufactured from polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC) [16]. While essential for maintaining sterility, these materials are non-biodegradable and accumulate rapidly in landfills. The COVID-19 pandemic amplified this crisis, generating millions of tonnes of contaminated plastic waste worldwide [17]. If not recycled through chemical or thermal valorisation, this plastic persists for decades, entering soils and aquatic systems as microplastics with toxic consequences [18].

Radioactive and Hazardous Waste

Though produced in smaller amounts, radioactive waste from diagnostic and therapeutic applications carries disproportionate risks. Items such as vials, syringes, and excreta from patients treated with isotopes like iodine-131 or technetium-99 require careful shielding and long-term storage to prevent exposure [19]. Alongside radioactive material, hazardous heavy metals like mercury from broken thermometers, cadmium from discarded batteries, and lead from protective shields



pose toxic, bioaccumulative, and neurotoxic effects if released into the environment [20].

Segregation and Collection Practices

The safe management of biomedical waste begins with segregation at source. International and national guidelines recommend colour-coded bins and bags—for instance, yellow for infectious waste, red for contaminated plastics, blue or white for sharps, and black for general discards. Proper segregation not only reduces risks but also lowers treatment costs by preventing unnecessary mixing of hazardous and non-hazardous materials [21]. Unfortunately, compliance remains inconsistent, especially in low-resource settings, where mixing of streams increases both public health risks and environmental burdens [22]. Ensuring effective segregation requires not just infrastructure but also continuous training, monitoring, and accountability mechanisms.

3. Existing Treatment and Disposal Methods

Biomedical waste treatment has historically relied on conventional strategies such as incineration, autoclaving, and deep burial. While these methods were once considered adequate for reducing immediate health risks, their environmental footprint and cost inefficiencies have made them increasingly controversial.

Incineration

Incineration remains one of the most widely used methods due to its ability to significantly reduce waste volume and destroy infectious agents at temperatures exceeding 800–1200 °C. However, the process is not without serious drawbacks. It emits dioxins, furans, polycyclic aromatic hydrocarbons, and heavy metals, all of which are associated with an increased risk of cancer, endocrine disruption, and

respiratory diseases [23]. Moreover, incinerator ash, often containing high concentrations of lead, cadmium, and mercury, must be disposed of in secure landfills, creating a secondary waste stream [24].

Autoclaving

Autoclaving is increasingly adopted in hospitals as a safer alternative for sterilizing infectious waste, sharps, and microbiological cultures. It uses saturated steam under pressure (121–134 °C), achieving sterilization without combustion. While effective for infectious materials, autoclaving cannot treat pharmaceuticals, cytotoxic drugs, or chemical residues, which remain hazardous post-treatment [25]. Additionally, its reliance on large volumes of electricity or steam makes it energy-intensive, limiting its suitability in resource-poor regions [26].

Deep Burial

In many rural or low-resource healthcare settings, deep burial is still practiced because of its simplicity and low cost. Waste is placed in pits at least two meters deep and covered with soil or lime to limit scavenging and odor. However, this practice carries significant risks of groundwater contamination and uncontrolled pathogen survival [27]. For these reasons, deep burial is discouraged by international agencies and permitted only under strictly defined conditions, usually in small rural facilities where no alternative exists.

Shortcomings of Conventional Methods

Though effective in reducing the bulk and immediate infectious hazards, these traditional practices share important limitations:

- Secondary pollution through toxic emissions and contaminated ash.



- High operational and infrastructure costs, particularly for incineration and autoclaving.
- Incomplete coverage, since chemical, cytotoxic, and radioactive wastes remain untreated.
- Occupational hazards for workers, particularly where segregation at source is weak [28].

Such challenges highlight the urgent need to shift toward sustainable alternatives based on recycling, energy recovery, and resource reclamation rather than mere disposal.

Regulatory Frameworks

International and national regulations increasingly stress sustainable biomedical waste management. The World Health Organization (WHO) issues global guidance on safe treatment and segregation standards [29]. In the United States, the Environmental Protection Agency (EPA) enforces strict emission standards under the Clean Air Act, mandating continuous monitoring of pollutants from incinerators [30]. The European Union's Waste Framework Directive (2008/98/EC) promotes waste minimization, recycling, and safe disposal, embedding the principles of the circular economy [31]. In India, the Central Pollution Control Board (CPCB) issued the Biomedical Waste Management Rules (2016, amended 2018), which made segregation at source, barcoding, and treatment at authorized facilities mandatory [32]. Despite these frameworks, challenges of compliance and infrastructure gaps remain a barrier in many developing nations.

4. Chemical Treatment Approaches

Chemical treatment technologies are among the most advanced approaches in biomedical waste management (Table 1&

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Figure 1). Unlike traditional thermal disposal, which is often criticised for producing secondary pollutants, chemical processes aim to neutralise pathogens, break down hazardous organics, and, in some cases, recover valuable resources. These methods are adaptable, ranging from basic disinfection of infectious waste to sophisticated catalytic recycling of plastics into fuels and feedstocks. Importantly, chemical treatments support the circular economy concept, transforming biomedical waste from an environmental problem into a potential resource.

Chemical Disinfection

Chemical disinfection is one of the oldest and most widespread methods for managing biomedical waste. Disinfectants such as sodium hypochlorite, chlorine dioxide, peracetic acid, hydrogen peroxide, and ozone mainly function by oxidising microbial cell walls, proteins, and nucleic acids, rendering pathogens non-viable [33,34]. Sodium hypochlorite (NaOCl) is cost-effective and efficient but produces chlorinated by-products like trihalomethanes, which are toxic and environmentally persistent [35]. Peracetic acid and hydrogen peroxide are relatively “cleaner” oxidants, leaving minimal residues, but they are less effective under high organic load conditions and require longer contact times [36]. Ozone can be generated on-site without the need for chemical transport, offering the advantage of no storage issues, but its instability limits storage and handling. Overall, chemical disinfection remains essential for liquid biomedical waste, sharps, and microbiological cultures, though its environmental impact mandates cautious application.

Alkaline Hydrolysis

Alkaline hydrolysis, often called tissue digestion, is increasingly recognised as a



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sustainable alternative to incineration for pathological waste and organic discards. This process uses sodium hydroxide (NaOH) or potassium hydroxide (KOH) at high temperature and pressure to break down proteins, lipids, and nucleic acids into sterile aqueous effluents [37]. Originally developed for disposing of animal carcasses and research specimens, alkaline hydrolysis is now being piloted in hospitals and academic laboratories [38]. Its major advantage lies in the fact that the effluent, after neutralisation, is biodegradable and can be safely discharged. Unlike incineration, it does not produce dioxins or heavy metals. However, alkaline hydrolysis requires specialised equipment and is unsuitable for plastics, metals, and large-scale mixed waste streams, which limits its universal adoption [39].

Solvent-Based Recovery of Plastics

With plastics comprising 30–40% of hospital waste, their recovery has become a research focus. Solvent-based recycling involves dissolving biomedical plastics such as PVC, PP, and PE in selective solvents like toluene, xylene, N-methyl-2-pyrrolidone (NMP), or dimethylformamide (DMF), followed by precipitation, filtration, and purification [40]. This process produces polymers of high purity, often comparable to virgin resins. It is particularly relevant for COVID-19 related PPE, which generated unprecedented amounts of disposable gowns, masks, and gloves [41]. However, this method is limited by the toxicity of organic solvents, the potential leaching of additives such as phthalates, and high operational costs. Additionally, strict decontamination procedures are required to ensure the biosafety of recycled plastics, which has thus far restricted large-scale implementation.

Catalytic Depolymerization and Solvolysis

Catalytic depolymerisation and solvolysis are advanced chemical valorisation techniques where plastics are broken down into monomers, fuels, or petrochemical feedstocks. In depolymerisation, catalysts such as zeolites, nickel, cobalt, or supported metal oxides speed up the breaking of long polymer chains under controlled temperatures [42]. Solvolysis, by contrast, uses solvents like methanol, ethanol, or supercritical water to enable chain scission, producing alcohols, glycols, or oligomers [43]. These processes offer the potential for closed-loop recycling, where biomedical plastics can be chemically recovered into the industrial economy. However, challenges such as process cost, catalyst deactivation, and energy demand still exist, limiting their use mostly to research and pilot-scale plants.

Plasma Pyrolysis with Catalysts

Among advanced methods, plasma pyrolysis is often regarded as the most comprehensive treatment for biomedical waste. By generating extremely high temperatures (up to 10,000 °C) through a plasma arc, the process decomposes complex biomedical waste into syngas ($H_2 + CO$) and vitrified slag. Catalysts such as Ni, Co, or ZSM-5 zeolites are used to reduce tar formation and enhance gas quality [44]. Plasma pyrolysis can process mixed waste streams — including plastics, sharps, and organic matter — without prior segregation. Unlike incineration, it emits negligible dioxins or furans, making it environmentally safer [45]. However, plasma pyrolysis is capital-intensive, energy-demanding, and requires trained operators, limiting its adoption mainly to tertiary hospitals and centralised treatment facilities in high-income countries.



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Table 1. Chemical Treatment Approaches for Biomedical Waste

Method	Principle	Chemicals / Catalysts Used	Applications	Advantages
Chemical Disinfection	Oxidation of microbial proteins and nucleic acids	NaOCl, ClO ₂ , H ₂ O ₂ , O ₃ , Peracetic acid	Sharps, liquid waste, laboratory cultures	Low cost, effective sterilization, globally practiced
Alkaline Hydrolysis	Hydrolysis of organic matter under alkali at high T & P	NaOH, KOH	Pathological waste, tissues, animal carcasses, lab samples	No toxic emissions, biodegradable effluent, complete pathogen destruction
Solvent-Based Recovery	Dissolution of polymers in solvents; recovery by precipitation	NMP, DMF, Toluene, Xylene	PPE kits, masks, gloves, IV sets, syringes	Produces near-virgin quality polymers, reduces plastic pollution
Catalytic Depolymerization & Solvolysis	Catalytic cleavage or solvent-assisted breakdown into monomers/fuels	Catalysts: Zeolites, Ni, Co, Mo; Solvents: Methanol, Ethanol, Supercritical water	Biomedical plastics (PP, PE, PVC)	Closed-loop recycling, yields high-value chemicals/fuels
Plasma Pyrolysis with Catalysts	High-T plasma arc + catalytic conversion into syngas + vitrified slag	Plasma torch; Catalysts: Ni, Co, ZSM-5, Activated carbon	Mixed biomedical waste (plastics, sharps, organics)	Minimal emissions, inert residue, energy recovery

5. Thermal & Physicochemical Recycling Approaches

Traditional chemical disinfection methods, though effective, are limited in their ability to handle heterogeneous biomedical waste streams such as plastics, pharmaceuticals, and complex mixtures (Table 2). This has led to increasing interest in thermal and

physicochemical recycling technologies, which not only sterilise waste but also enable energy and material recovery. These methods offer a bridge between environmental protection and resource circularity, making them central to the vision of sustainable healthcare waste management.

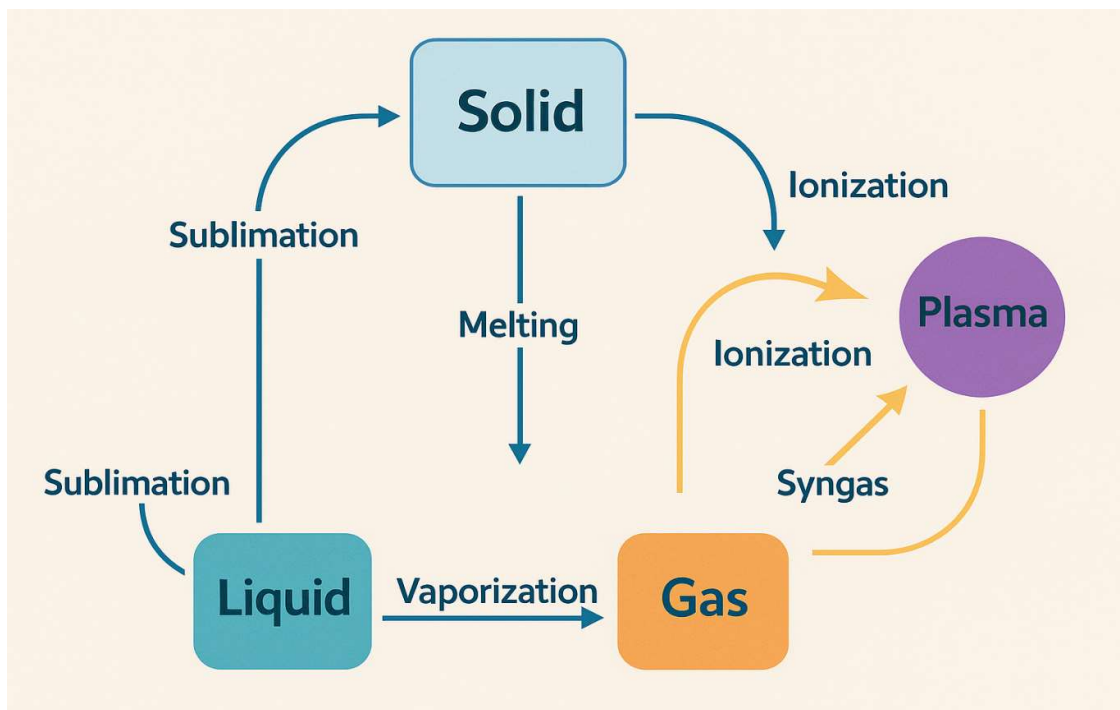


Figure 1: Chemical Treatment Approaches for Biomedical Waste

Microwave Irradiation Sterilization

Microwave irradiation has emerged as a promising non-incineration sterilization technique for biomedical waste. Operating typically at 2,450 MHz, microwaves induce dielectric heating by exciting polar molecules such as water, which in turn generates localized high temperatures capable of denaturing proteins and nucleic acids [46]. This process effectively inactivates bacteria, viruses, and spores in infectious waste, sharps, and laboratory discards. Some systems also integrate steam or chemical additives (e.g., H_2O_2 vapour) to improve penetration and sterilisation efficiency [47]. The major advantages include no dioxin/furan emissions, compact equipment, and relatively low costs compared to incineration. However, drawbacks include the requirement for pre-shredding, dependency on waste moisture, and

inability to degrade pharmaceuticals or cytotoxic agents [48].

Pyrolysis and Gasification

Pyrolysis and gasification are thermochemical recycling methods designed to transform biomedical plastics and organic waste into useful fuels.

- Pyrolysis operates under anaerobic or low-oxygen conditions (350–600 °C), breaking down polymers such as polypropylene (PP), polyethylene (PE), and PVC into liquid oil, syngas, and char [49]. Catalysts such as zeolites, alumina, and silica-alumina are often added to enhance oil yield and reduce tar formation [50].
- Gasification, performed at 800–1000 °C with limited oxygen or steam, generates a syngas mixture of H_2 , CO , CH_4 , and CO_2 , which can be used in



power generation or upgraded into liquid fuels [51].

Compared to incineration, both methods produce fewer toxic by-products while enabling energy recovery. Limitations include high capital and operational costs, tar management in gasification, and feedstock pre-treatment requirements. Nevertheless, these approaches are increasingly considered as circular economy-compatible solutions for hospital plastic waste, particularly after the surge in disposable PPE during the COVID-19 pandemic [52].

Supercritical Water Oxidation (SCWO)

Supercritical water oxidation (SCWO) is an advanced physicochemical process that exploits the properties of water beyond its critical point (374 °C, 22.1 MPa). At this state, water behaves both like a gas and a liquid, dissolving organic molecules while enabling rapid oxidation [53]. Waste streams containing antibiotics, cytotoxic drugs, phenolic compounds, or hospital effluents with high COD can be entirely oxidised into CO₂, H₂O, and inorganic salts within seconds [54]. Oxidants such as air, O₂, or H₂O₂ are often added to accelerate reaction rates [55]. SCWO achieves nearly 100% destruction efficiency without producing dioxins or furans. However, issues such as corrosion of reactor walls, salt deposition, and high maintenance costs present significant technical challenges [56]. Currently, research focuses on

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titanium alloys, nickel-based superalloys, and ceramic linings to enhance corrosion resistance.

Photocatalytic Degradation of Pharmaceutical Residues

Hospital wastewater contains a cocktail of pharmaceuticals, antibiotics, hormones, and cytotoxic drugs, which persist even after conventional treatment. Photocatalysis has emerged as a sustainable method to degrade these residues using semiconductor catalysts such as TiO₂, ZnO, WO₃, and doped nanomaterials [57]. When irradiated with UV or visible light, these catalysts generate reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and superoxide ions (O₂•⁻), which mineralize organic pollutants into CO₂ and water [58]. Photocatalytic degradation has shown promising results for antibiotics (amoxicillin, ciprofloxacin), antineoplastics (cyclophosphamide), and endocrine disruptors [59].

Recent advancements include doping TiO₂ with metals (Ag, Fe, Cu) or non-metals (N, C) to enhance visible-light activation, as well as immobilised catalyst systems to prevent secondary contamination [60]. Despite its advantages, limitations include partial degradation, intermediate formation, and catalyst deactivation. Large-scale application requires integration with membrane reactors, ozonation, or solar photocatalysis.



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Table 2. Thermal & Physicochemical Recycling Approaches

Method	Principle	Chemicals / Catalysts Used	Applications	Advantages
Microwave Irradiation	Dielectric heating via microwaves (2,450 MHz) generates localized sterilization	Water molecules (for heating), optional H ₂ O ₂ vapor or steam	Infectious waste, sharps, lab samples	Compact, low emissions, effective sterilization
Pyrolysis	Anaerobic thermal decomposition (350–600 °C)	Catalysts: Zeolites, alumina, silica-alumina	Plastics (PPE, syringes, IV sets)	Produces liquid oil, syngas, char; energy recovery
Gasification	Partial oxidation at 800–1000 °C with limited O ₂ /steam	Gasifying agents: O ₂ , steam, air; Catalysts: Ni-based	Biomedical plastics, PPE, contaminated disposables	Produces syngas (H ₂ , CO) for fuel/electricity
SCWO	Oxidation in water above critical point (374 °C, 22.1 MPa)	Oxidants: O ₂ , H ₂ O ₂ , air; Corrosion-resistant alloys (Ti, Ni)	Pharmaceutical residues, cytotoxic drugs, liquid biomedical waste	Nearly 100% destruction, no toxic emissions
Photocatalysis	Semiconductor catalysts activated by UV/visible light produce ROS	TiO ₂ , ZnO, WO ₃ , doped TiO ₂ (Ag, N, C)	Hospital wastewater, antibiotics, cytotoxic residues	Complete mineralization, solar compatibility

6. Resource Recovery and Circular Economy Approaches

In recent years, the paradigm of biomedical waste management has shifted from a “disposal mindset” toward a circular economy framework, where waste is viewed as a potential resource stream. This transition is essential not only to reduce environmental burdens but also to conserve energy, recover critical materials, and generate economic value. Central strategies include waste-to-energy plants, recycling of plastics into resins or monomers,

recovery of precious metals from medical devices and diagnostic films, and valorization of organic waste into compost or biogas. Together, these innovations illustrate how biomedical waste can be transformed from an environmental liability into a sustainable asset (Table 3).

Waste-to-Energy (WtE) Plants

Waste-to-energy technologies are among the most mature pathways for biomedical waste valorization. In such facilities, waste is incinerated, pyrolyzed, or gasified, and



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the released thermal energy is harnessed for steam, electricity, or heating [61]. Syngas from gasification and pyrolysis can further be refined into liquid fuels, hydrogen, or industrial chemicals [62]. Importantly, modern WtE plants are equipped with flue gas cleaning systems, scrubbers, and catalytic converters that drastically reduce toxic emissions, aligning with WHO and EU emission standards [63].

The advantages of WtE include volume reduction, pathogen destruction, and energy generation, making it particularly suitable for urban hospitals and centralized treatment facilities. However, the capital-intensive nature of WtE infrastructure, high operational costs, and reliance on advanced emission control technologies limit its adoption in developing nations [64]. Moreover, concerns remain over dioxins, furans, and heavy metals in fly ash, necessitating secure ash disposal or vitrification.

Plastic Recycling into Resins or Monomers

Biomedical plastics—including syringes, IV sets, PPE kits, and disposable gowns—constitute nearly one-third of hospital waste. Recycling these plastics represents a crucial pathway for circularity.

- Mechanical recycling involves collection, shredding, washing, and re-extrusion into resins for use in low-grade applications such as packaging or construction [65].
- Chemical recycling, by contrast, employs pyrolysis, solvolysis, depolymerization, or catalytic hydrogenolysis to recover monomers (e.g., styrene, ethylene, terephthalic acid) and feedstocks [66,67].

During the COVID-19 pandemic, recycling strategies were especially emphasized as

billions of PPE units led to an unprecedented plastic footprint [68]. Challenges, however, include contamination with blood or drugs, polymer degradation after multiple cycles, and cost-intensive sterilization requirements [69]. Nevertheless, with advances in enzymatic depolymerization, solvent-based purification, and nanocatalysts, biomedical plastic recycling is gradually evolving into a viable industrial practice.

Recovery of Precious Metals

Biomedical equipment and diagnostic tools often contain critical and precious metals. For example, silver (Ag) is widely used in X-ray films, wound dressings, and antimicrobial coatings, while gold (Au) and platinum (Pt) are found in biosensors, pacemakers, catheters, and electrodes [70]. Recovery techniques include:

- Hydrometallurgy (acid leaching with HCl, HNO₃, or aqua regia),
- Pyrometallurgy (smelting, roasting, plasma refining), and
- Bioleaching using microorganisms such as *Acidithiobacillus ferrooxidans* that mobilize metals [71].

Recovered Ag can be reused in medical imaging or electronics, while Au and Pt are highly valued in catalysis, electrochemistry, and implantable devices [72]. Limitations include the use of toxic reagents (e.g., cyanides, nitric acid), high energy consumption, and waste sludge generation. Green alternatives such as biosorption, plant-based extraction, and ionic liquids are under investigation to make metal recovery more sustainable [73].

Organic Waste Valorization: Compost and Biogas



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A significant portion of biomedical waste—particularly from hospital kitchens, biodegradable disposables, and organic dressings—can be valorized into compost or biogas.

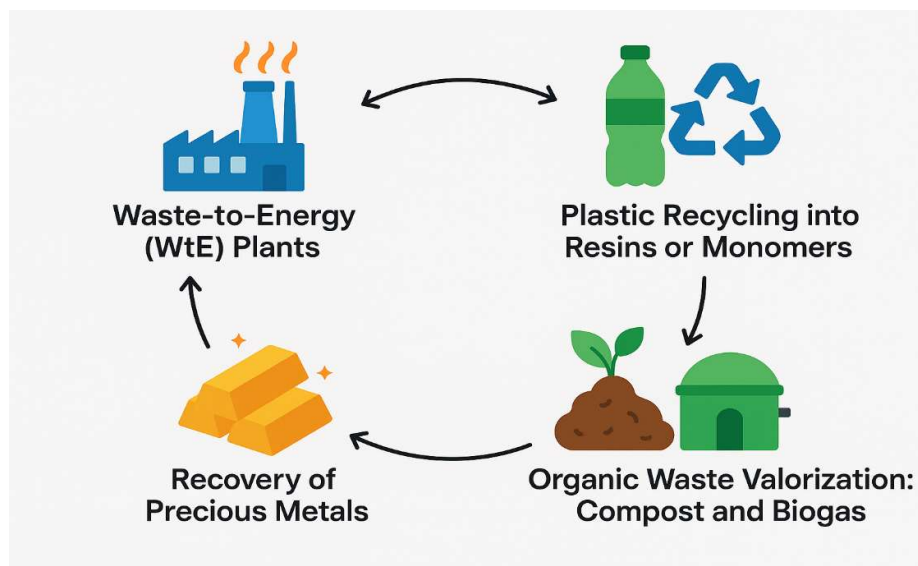
- Anaerobic digestion (AD) breaks down organic waste into biogas ($\text{CH}_4 + \text{CO}_2$) and a nutrient-rich digestate that can be used as fertilizer [74].
- Composting converts biodegradable waste into humus-like material that

improves soil fertility and reduces reliance on chemical fertilizers.

Co-digestion of hospital organic waste with municipal sludge has been shown to enhance methane yields, making it a viable renewable energy pathway [75]. However, poor segregation may introduce plastics, sharps, or pharmaceuticals into compost/AD feedstocks, raising safety concerns. Therefore, pretreatment and strict segregation are prerequisites for safe adoption.

Table 3. Resource Recovery & Circular Economy Approaches

Approach	Resource Recovered	Applications	Advantages
Waste-to-Energy (WtE)	Heat, electricity, syngas	Hospital power supply, industrial feedstocks	Handles large volumes, energy recovery, pathogen destruction
Plastic Recycling	Resins, monomers (styrene, ethylene, terephthalic acid)	Packaging, textiles, medical supplies	Reduces plastic footprint, supports circular polymer economy
Precious Metal Recovery	Silver, gold, platinum	Electronics, catalysts, implants, medical imaging	High economic value, conserves critical resources
Organic Waste Valorization	Biogas ($\text{CH}_4 + \text{CO}_2$), compost	Renewable energy, fertilizer	Reduces GHG emissions, sustainable farming input





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Figure 2: Thermal and Physicochemical Recycling Approaches for Biomedical Waste

7. Advantages of Advanced Treatment Approaches

The adoption of advanced biomedical waste treatment technologies offers several critical benefits that extend beyond traditional disposal. First and foremost, they significantly reduce infection risks, safeguarding both healthcare workers and the wider community by ensuring effective pathogen inactivation [76]. Unlike conventional incineration or deep burial, modern methods minimize the chances of cross-contamination and disease outbreaks.

Equally important is their capacity for energy and resource recovery. Technologies such as pyrolysis, gasification, and plasma pyrolysis not only sterilize waste but also generate syngas, fuels, or electricity, directly contributing to energy security [77]. Plastic depolymerization and metal recovery processes create secondary raw materials, feeding back into industrial supply chains and reducing reliance on virgin resources.

Another major advantage is volume reduction. Processes like SCWO, plasma pyrolysis, and autoclaving reduce the mass of waste by up to 80–95%, easing the burden on landfills [78]. Finally, advanced biomedical waste management contributes to sustainable healthcare systems, directly aligning with the United Nations Sustainable Development Goals (SDGs 3, 6, 7, 12, and 13) by promoting good health, clean water, affordable clean energy, responsible consumption, and climate action [79].

8. Limitations and Challenges

Despite their promise, advanced treatment technologies face significant barriers to widespread implementation. The foremost challenge lies in their high capital and operational costs, which restrict adoption in

low- and middle-income countries where healthcare budgets are already stretched [80]. Technologies like plasma pyrolysis, SCWO, and catalytic depolymerization demand specialized infrastructure, skilled operators, and reliable energy inputs, making them impractical in decentralized or rural settings [81].

Equally critical is the need for infrastructure supporting segregation at source. Even the most advanced technology cannot function optimally without proper upstream sorting of infectious, plastic, chemical, and radioactive waste fractions. Poor segregation leads to inefficient treatment, damage to equipment, and safety hazards [82].

There is also a risk of incomplete treatment or secondary pollutants. For instance, pyrolysis may leave residual char, gasification often struggles with tar control, and photocatalysis may generate toxic intermediates [83]. Moreover, regulatory fragmentation remains a significant barrier, as countries adopt varied standards and guidelines. The absence of global standardization complicates cross-border collaboration and technology transfer [84].

9. Future Perspectives

Looking ahead, the future of biomedical waste management lies in green, intelligent, and globally harmonized solutions. Green chemistry innovations, such as biodegradable disinfectants and non-toxic solvents, will replace chlorine-based agents and reduce harmful by-products [85]. Similarly, nanotechnology-based catalysts (e.g., doped TiO_2 , graphene-supported metals) hold promise for efficient degradation of plastics, pharmaceuticals, and organic residues under milder conditions [86].



Digital innovations will also play a crucial role. Artificial intelligence (AI), blockchain, and Internet of Things (IoT)-enabled systems are expected to transform waste tracking, segregation, and compliance monitoring. Smart sensors can detect contamination levels, while AI-driven predictive models can optimize treatment efficiency and reduce operational costs [87].

At the policy level, strengthened regulatory frameworks and international harmonization are urgently needed. Global agreements similar to the Basel Convention, but specifically tailored for biomedical waste, could ensure safe cross-border movement, uniform emission standards, and equitable access to technology [88]. With integrated strategies, biomedical waste could shift from being a hazardous liability to a driver of sustainable healthcare and circular economies.

Conclusion

Biomedical waste management is undergoing a critical transformation from mere disposal toward sustainable resource recovery systems. Advanced chemical, thermal, and physicochemical approaches have shown remarkable promise in reducing infectious hazards, recovering valuable energy and materials, and aligning healthcare systems with global climate and sustainability goals. Waste-to-energy plants, plastic recycling, and precious metal recovery illustrate how biomedical discards can fuel the circular economy, while organic waste valorization further broadens renewable energy pathways. Yet, widespread adoption remains constrained by high capital costs, infrastructure gaps, and lack of global regulatory coherence. To unlock their full potential, these technologies must be integrated with green chemistry principles, nanotechnology-

driven innovations, and digital/AI-enabled monitoring frameworks. Strengthened international collaboration and policy harmonization will be essential in scaling up solutions equitably across regions. Ultimately, transforming biomedical waste into usable resources represents not only a technological challenge but also a moral imperative for sustainable healthcare.

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