Rouf Ahmad Bhat
Gowhar Hamid Dar
Younis Ahmad Hajam *Editors*

Zero Waste Management Technologies

Springer

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Editors
Rouf Ahmad Bhat
Department of School Education
Government of Jammu and Kashmir
Srinagar, Jammu and Kashmir, India

Younis Ahmad Hajam
Sant Baba Bhag Singh University
Jalandhar, Punjab, India

Gowhar Hamid Dar
Department of Environmental Science
Government Degree College Kulgam,
Higher Education Department
Srinagar, Jammu and Kashmir, India

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In a world where foes and friends entwine,
Enemy and environment, a tale to define.
Humans stand as stewards of this earthly plane,
To conquer challenges, we must break the chain.
Zero waste management, our mission's decree,
Turn enemy into ally, set our world free.
For when we unite, in this common endeavour,
We protect the environment, cherish it forever.

—Ibtihaaj Bilal

Preface

In a world where the delicate balance of our planet's ecosystems is under threat and our finite resources are being depleted at an alarming rate, the concept of "zero waste" has emerged as an encouragement to protect the environment. This book delves deep into the heart of this movement, exploring the myriad strategies that empower individuals, communities, and industries to transition towards a more sustainable and harmonious way of living. The pages that follow are not just about waste reduction; they embody a philosophy that challenges the very foundations of our consumer-driven society. The journey towards zero waste is not a mere trend or a passing fad—it is a profound shift in perspective, a transformative approach that demands a re-evaluation of how we produce, consume, and dispose. In "Zero Waste Strategies", we embark on an exploration of innovative concepts, pragmatic methodologies, and inspiring success stories from around the globe. We will navigate through the complex web of challenges and opportunities, from reimagining product design to redefining supply chains, from advocating for policy changes to fostering a cultural shift in attitudes towards consumption and disposal. This book is a treasure trove of insights, a toolkit of ideas, and a source of inspiration for everyone seeking to contribute to a world where waste is minimized, resources are conserved, and the health of our planet is safeguarded for future generations. Whether you are an environmental enthusiast, a curious learner, a business leader, or a policymaker, "Zero Waste Strategies" offers something for you. It is an invitation to explore a new way of thinking, a call to action to embrace sustainability as a core value, and a reminder that our collective choices today shape the world we pass on to tomorrow. As you journey through these pages, may you be inspired to not only adopt Zero Waste Strategies in your own life but to also champion them in your communities and beyond. The time to act is now, and the power to make a difference lies within each of us. Together, let us embark on this transformative path towards a future where waste is but a distant memory, and the

concept of “waste not, want not” resonates with renewed vigour. Welcome to “Zero Waste Strategies”. Your adventure towards a more sustainable world starts here.

Srinagar, India — Dr. Rouf Ahmad Bhat
Srinagar, India — Dr. Gowhar Hamid Dar
Jalandhar, India — Dr. Younis Ahmad Hajam

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About This Book

This volume *Zero Waste Management Technologies* highlights cutting-edge research on zero waste management and the associated effects of waste on the environment. Predominantly, it focuses on the challenges of dealing with the amassed production of waste and the cumulative impact of increasing waste on the biosphere. Different sections of this book focus on the comprehensive overview of the technological advancements driving the zero waste movement. Furthermore, it explores innovations in waste reduction, recycling, and repurposing, from a global perspective, examining the diverse cultural, social, and economic factors influencing the adoption of Zero Waste Strategies worldwide. In addition, it discusses the challenges and opportunities inherent in promoting a unified global effort towards sustainable resource management. The book serves as a comprehensive roadmap for those seeking to embrace the transformative power of zero waste strategies, making it essential reading for individuals, communities, and industries passionate about fostering sustainable resource management and preserving the planet for future generations.

Key Features:

- Highlights the issues and challenges in achieving a zero waste society.
- Offering a roadmap for policymakers, business setups, and individuals to overcome the hurdles and providing insights into the potential future trajectories of the zero waste movement.
- Investigation with respect to powerful technologies regarding waste to revenue and waste to energy.
- Providing advanced biotreatment technologies for the reduction of the quantum of waste.

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About the Editors

Dr. Rouf Ahmad Bhat (Ph.D.) has pursued his doctorate at Sher-e-Kashmir University of Agricultural Sciences and Technology Kashmir (Division of Environmental Sciences) and presently working in the Department of School Education, Government of Jammu and Kashmir. Dr. Bhat has been teaching graduate and postgraduate students of environmental sciences for the past three years. He is an author of more than 55 research articles (h-index 30; i-index 44; total citation 2500) and 40 book chapters and has published more than 40 books with international publishers (*Springer, Elsevier, CRC Press Taylor and Francis, Apple Academic Press, John Wiley, IGI Global*). He has his specialization in limnology, toxicology, phytochemistry, and phytoremediation. Dr. Bhat has presented and participated in numerous state, national, and international conferences, seminars, workshops, and symposiums. Besides, he has worked as an associate environmental expert in World Bank-funded Flood Recovery Project and also the environmental support staff in the Asian Development Bank (ADB)-funded development projects. He has received many awards, appreciations, and recognition for his services to the science of water testing, air, and noise analysis. He has served as an editorial board member and a reviewer of reputed international journals. Dr. Bhat is still writing and experimenting with diverse capacities of plants for use in aquatic pollution remediation.

Dr. Gowhar Hamid Dar (Ph.D.) is currently working as Assistant Professor in Environmental Science at Sri Pratap College, Cluster University Srinagar, Department of Higher Education (J&K). He has a Ph.D. in Environmental Science with specialization in Environmental Microbiology (Fish Microbiology, Fish Pathology, Industrial Microbiology, Taxonomy, and Limnology). He has been teaching postgraduate and graduate students for the past many years at Postgraduate Department of Environmental Science, Sri Pratap College, Cluster University Srinagar. He has more than 70 research articles (**h**-index **16**; **i**-index **22**; total citation **>950)** in international and national journals of repute and more than 20 books with international publishers (***Springer, Elsevier, CRC Press Taylor and Francis, Apple Academic Press, John Wiley, IGI Global***) to his credit. Moreover, he is supervising a number of students for the completion of degrees. He has been working on the isolation, identification, and characterization of microbes, their pathogenic behaviour and impact of pollution on development of diseases in fish fauna for the last several years. He has received many awards and appreciations for his services towards the science and development. Besides, he also acts as a member of various research and academic committees. Further, Dr. Dar is Principal Investigator and Co-Principal Investigator for different R&D projects sanctioned by Government of India and Government of Jammu and Kashmir.

Dr. Younis Ahmad Hajam holds a doctorate in Zoology from Guru Ghasidas Vishwavidayalaya (A Central University), Bilaspur, Chhattisgarh, India. He is currently working as Assistant Professor in the Department of Life Sciences and Allied Health Sciences, Sant Baba Bhag Singh University, Padhiana, Jalandhar, Punjab, India. Formerly, Dr. Younis Ahmad had worked as an assistant professor and head of Department of Zoology, Career Point University, Hamirpur, Himachal Pradesh, India. He is teaching undergraduate and postgraduate and doctorate students. Dr Younis Ahmad has published 42 research papers in leading national and international journals, 45 book chapters, and four (10) national proceeding. Dr. Younis Ahmad has published 8 books as an editor in Springer, Apple Academic

Press, NOVA Science Publishers, Taylor and Francis, etc. He has guided 5 M.Sc. students under thesis mode and 33 M.Sc. students under project mode. Dr. Younis Ahmad has completed one major research project (PI) and three projects under HP Chief Minister Startup Scheme. Dr. Younis Ahmad has also served as Junior Research Fellow (JRF) at Zoology, Guru Ghasidas Central University, Bilaspur, Chhattisgarh, India. He has presented his research work in more than 35 national and international conferences; Dr. Younis Ahmad has attended more than 30 national and international conferences and 5 workshops. He has organized various conferences, seminars, workshops, and webinars at the national and international levels. Dr. Younis Ahmad has also delivered invited lectures in international conference. He has received national award for his contributions in biological science. He is an editorial member of various international journals and is also a member of the Asian Council of Science editors.

Chapter 1
A Comprehensive Review on the Development of Zero Waste Management

Zulaykha Khurshid, Md. Osama Zubair, and Humaira

Abstract A revolutionary and proactive strategy to address the escalating global waste predicament and corresponding negative environmental effects is Zero Waste Management. The notion of zero waste management and its importance in facilitating sustainable development goals are thoroughly explored in this chapter. We start by defining zero waste management and its fundamental tenets, which emphasize waste reduction, reuse, and recycling within a framework of the circular economy. Analysis of the strong connection between zero waste management and sustainable development is done, demonstrating the advantages of implementing such practices on the social, economic, and environmental fronts. The hierarchy of waste management systems is shown by key ideas, using the waste hierarchy concept. We study the technological advancements that are advancing zero waste management, including waste-to-energy technology, sophisticated recycling methods, and intelligent waste management systems. The chapter also explores the crucial legal and policy foundations that support and advance zero waste programmes at the municipal, state, and federal levels. The social and behavioural components of zero waste management are also covered, with a focus on the need of community involvement and education. The chapter also discusses new trends, problems, and possibilities in the quest for a more sustainable waste management ecosystem, providing insightful information on the prospects for zero waste management in future. The thorough analysis provided in this chapter helps readers gain a greater knowledge of zero waste management and its potential to usher in a more affluent and environmentally friendly future. Societies may create the conditions for a sustainable and regenerative future by implementing this comprehensive strategy and rethinking garbage as a precious resource.

Z. Khurshid (✉)
Department of Environmental Science/Centre of Research for Development, University of Kashmir, Srinagar, J&K 190006, India
e-mail: Zulaykhazehra@gmail.com

Md. O. Zubair
Centre for Nanoscience and Nanotechnology, Jamia Millia Islamia, New Delhi 110025, India

Humaira
Centre of Research for Development, University of Kashmir, Srinagar, J&K 190006, India

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1 Introduction

The consequences of waste generation and environmental degradation are only becoming worse (Abbas et al., 2019; Rios et al., 2019). Zero waste management has emerged as a potent and revolutionary solution. This comprehensive and sustainable approach has drawn international attention and received broad support from politicians, companies, communities, and individuals alike in the face of growing worries about resource depletion, pollution, and climate change (Awasthi, 2023; Bhat et al., 2021: Polettini, 2012). Zero waste management's primary goal is the elimination of waste via the use of a thorough, integrated system that places an emphasis on resource conservation and recovery. Zero waste promotes a circular economy where materials are continually reused, recycled, or renewed to minimize their environmental effect, in contrast to typical linear waste management, which uses a "take-make-dispose" approach (Ibrahim, 2020; Lehmann, 2011). This style of thinking is in line with the pressing need to change our disposable culture into one that prioritizes sustainability, effectiveness, and long-term resilience. According to Tang et al. (2022), Usapein and Chavalparit (2014) and Mancini et al. (2019), expanded producer responsibility, waste reduction, product redesign, and promoting environmentally friendly consumer choices are only a few of the many acts covered by the zero waste principles. The understanding that waste is not an unavoidable outcome of human activity but rather an effect of ineffective systems and unsustainable practises is at the core of this paradigm shift (Bhat et al., 2012). Zero waste management aims to disrupt the current quo and transform how society views and manages its wasted materials by reframing garbage as a valuable resource (Diliberto et al., 2020; Luidold, 2019). Numerous communities, businesses, and cities around the globe have started along the path to zero waste, setting ambitious goals and putting creative plans into practise to reduce waste and optimize resource use (Eriksen et al., 2019; Lai et al., 2022). Zero waste provides benefits for economic growth, social well-being, and a shared commitment to building a greener, more sustainable future in addition to protecting the environment (Khurshid & Khurshid, 2022). By examining zero waste management's key principles, methodologies, policy frameworks, and the different factors that influence its successful implementation, this chapter aims to provide an in-depth analysis of the practise in this context (Larrain et al., 2022; Zaman & Ahsan, 2019). By examining the environmental, financial, and social advantages of switching to zero waste systems, we hope to show how significantly this strategy can contribute to the development of a more sustainable and circular society (Diliberto et al., 2020; Mancini et al., 2019; Tang et al., 2022; Usapein & Chavalparit, 2014). Through fostering stakeholder engagement and funding state-of-the-art waste treatment technologies, this chapter will highlight the critical role that

zero waste management plays in constructing a responsible and sustainable future for our planet (Awasthi, 2023; Eriksen et al., 2019; Ibrahim, 2020; Khurshid & Khurshid, 2022; Lai et al., 2022; Larrain et al., 2022; Lehmann, 2011; Luidold, 2019; Polettini, 2012; Zaman & Ahsan, 2019). People from all walks of life are united by the paradigm-changing concept of zero waste management in their shared desire to preserve the Earth's resources for future generations. Together, we set out on a journey to a world without waste—a world where garbage is no longer considered as a nuisance but rather as a chance for renewal, creativity, and a more in tune way of life with our great planet. Zero waste management is presently at the top of agendas for sustainable development due to the urgent need to find answers to the world's environmental concerns.

2 Definition of Zero Waste Management

The term "zero waste management" is an interdisciplinary and transformational strategy that aims to eliminate or drastically reduce trash creation while implementing eco-friendly procedures for handling the leftover garbage (Bertanza et al., 2018; Lange, 2021). This paradigm shift, which embraces the concepts of a circular economy, questions the linear "take-make-dispose" model of resource consumption and places a focus on waste reduction, material recovery, and sustainable production and consumption patterns (Ibrahim, 2020; Yao et al., 2022) (Fig. 1).

Zero waste management is fundamentally based on the understanding that waste is not an inevitable byproduct of human activity but rather results from inefficiencies in the existing system (Khurshid, 2019). The end goal is to completely rethink the waste management process to maximize resource recovery, reduce the environmental effect, and move us towards a more sustainable future (Abbas et al., 2019; Flowers & Linderman, 2003). Zero waste management employs a comprehensive strategy made up of several activities to achieve this lofty goal. These approaches include of reducing trash production at the source, encouraging responsible consumer behaviour, implementing state-of-the-art waste treatment technology, encouraging expanded producer responsibility, and educating the general public about good waste management practises (Lehmann, 2011). The transformational viewpoint of considering waste as a useful resource, as opposed to the conventional perception of waste as a burden, is a basic principle behind zero waste management (Mahongnao et al., 2023). Zero waste management, which embraces this paradigm change, deliberately uses cutting-edge methods like recycling, composting, and other recovery strategies to maximize the potential of waste materials (Pietzsch et al., 2017). The system becomes intrinsically circular and supports sustainable and regenerative practises by reintegrating garbage into the economic cycle as valuable resources (Bolton & Rousta, 2019; Portugaise et al., 2023).

Zero waste management is essentially a proactive and dynamic response to the problems of waste creation and environmental deterioration (Bhat et al., 2018b). Societies may envisage and work towards a world without waste by totally adopting

Fig. 1 Facets of zero waste management

this comprehensive and holistic approach. In order to lead mankind towards a more robust and peaceful cohabitation with our planet, this future will be characterized by judicious resource conservation, minimized environmental impact, and a persistent adherence to the principles of sustainability.

3 Zero Waste Management and Sustainable Development

By addressing the environmental, social, and economic components of sustainability, zero waste management plays a vital part in proceeding towards sustainable development goals (Brancoli & Bolton, 2019; Leal Filho et al., 2019). Adopting zero waste practices is indispensable to decreasing the undesirable consequences related to garbage disposal with increase in waste generation rates (Bhat et al., 2013, 2014; Masud et al., 2019). Societies and organizations may considerably cut their carbon footprints, conserve natural resources, and protect ecosystems by swapping to a zero waste management approach. Endorsement for the circular economy is one of the

crucial pillars of zero waste management. In order to make the most of resource efficiency and cut waste generation, this paradigm change places a significant importance on reducing, reusing, and recycling materials in a closed-loop arrangement (Corsten et al., 2013; Rios et al., 2019). Zero waste management approaches reduce energy usage and greenhouse gas emissions during manufacturing by curtailing the extraction of raw materials (Gutberlet, 2015; Yang, 2022). Moreover, zero waste management supports sustainable production and consumption patterns by advocating societies, organizations, and industrial sectors to reassess their consumption arrays and implement eco-friendly alternates (Shukhla & Khan, 2022). This eco-friendly approach fosters the designing and manufacture of long-term, repairable, and recyclable stuffs (Haapala et al., 2013). Also, efficient waste categorization and assemblage systems allow for the recovery and recycling of valuable materials thereby minimizing their termination as useless garbage. Reduction in the waste being discarded into the landfills and incinerators can help in conservation of natural resources besides minimizing the discharge of hazardous pollutants into the environment, and curtail exploitation of raw materials (Bartl, 2011; Rios et al., 2019; Shukla & Khan, 2022). Zero waste management has other recompenses for the society as well as the economy besides environment (Pires & Martinho, 2019). Zero waste management practices lift local economies and improve standard of living particularly in those areas which are dependent on this waste by yielding employment opportunities in the collection, recycling and resource recovery dealings (Silva et al., 2020; Zaman & Ahsan, 2019). By taking considerable measures for decreasing waste generation and improving on resource recovery, many businesses and marginal communities can earn money from the sale of recycled materials. Besides this, the establishment of innovative business models and technological advancements for management of waste promotes economic growth and generates additional market prospects (Abbas et al., 2019; Khurshid & Khurshid, 2022). Zero waste management also follows the circular economy approach principles by making the economy more robust, sustainable, and lesser reliant on limited resources (Eriksen et al., 2019; Silva et al., 2020). However, working towards zero waste management objectives at the international, national as well as at municipal levels necessitates the amalgamation and advancement of zero waste activities through all-inclusive waste management policies (Anawar et al., 2019; Pietzsch et al., 2017). By filling customer demands for sustainability and environmental accountability, implementing zero waste management practices provides ventures for several sectors to simplify production processes, minimize material waste, and develop their status (Corsten et al., 2013; Usapein & Chavalparit, 2014). By tackling waste-related problems and adopting responsible resource management, zero waste management acts as a driving force for achieving sustainable development goals. Governments, businesses, communities, and individuals must work collectively with the aim of embracing and putting into practice the zero waste management principles in order to achieve this objective. With a focus on resource efficiency, waste reduction, and social cohesion with the environment, it offers a direction to a green and prosperous future.

4 Key Concepts and Principles of Zero Waste Management

The goal of zero waste management is to minimize waste generation, maximize resource recovery, and ultimately eliminate the need for landfills and incineration. It is based on a number of fundamental ideas and tenets that guide how it is used (Pires & Martinho, 2019; Yang et al., 2023). Let us examine these ideas and guidelines in further detail:

i. **Waste prevention**: The primary goal of zero waste management is to prevent waste from being generated in the first place. This involves promoting sustainable production and consumption practices, encouraging the design of products with extended lifespans and recyclability, and minimizing packaging waste. By focusing on waste prevention, the overall volume of waste can be significantly reduced (Abbas et al., 2019).
ii. **Circular economy**: Zero waste management aligns with the principles of a circular economy, where resources are kept in use for as long as possible through recycling, reusing, and repurposing. Instead of the traditional linear "take-make-dispose" model, a circular economy seeks to close the loop, creating a system where waste is seen as a valuable resource (Quicker et al., 2020; Yang, 2022).
iii. **Source separation and collection**: An essential aspect of zero waste management is the separation of waste at the source. This involves encouraging households, businesses, and industries to sort their waste into different categories such as recyclables, organic waste, and non-recyclables. Source separation facilitates efficient recycling and resource recovery processes (Zlamparet et al., 2018).
iv. **Extended producer responsibility (EPR)**: EPR is a key principle that holds producers responsible for the entire life cycle of their products, including the management of waste generated from those products. By implementing EPR programmes, manufacturers are incentivized to design products with a focus on recyclability and reusability (Franco-García et al., 2019; Tsai et al., 2013).
v. **Recycling and resource recovery**: Zero waste management prioritizes recycling and resource recovery as a means to minimize waste sent to landfills and incinerators. By recycling materials, valuable resources are conserved, reducing the need for new raw materials and lowering environmental impacts (Rios et al., 2019).
vi. **Composting**: Organic waste, such as food scraps and yard trimmings, is a significant component of municipal waste. Composting is an essential process in zero waste management, where organic waste is converted into nutrient-rich compost, which can be used to enrich soil and support sustainable agriculture (Hameed et al., 2021; Zlamparet et al., 2018).
vii. **Reuse and repair**: Encouraging the reuse and repair of products is fundamental to zero waste management. Instead of discarding items, the goal is to extend their lifespan by repairing and refurbishing them, reducing the overall demand for new products (Bolton & Rousta, 2019; Polettini, 2012).

viii. **Redesigning products and packaging**: Zero waste management advocates for product and packaging design that prioritizes sustainability. This involves using materials that are easily recyclable, reducing single-use plastics, and adopting innovative packaging solutions that minimize waste (Abbas et al., 2019; Bhat et al., 2018a; Hickel et al., 2013).

ix. **Education and awareness**: Public education and awareness play a crucial role in zero waste management. By informing and engaging communities about the importance of waste reduction and sustainable practices, individuals can make informed choices and actively participate in waste reduction efforts (Korhonen & Koivisto, 2007; Ma et al., 2017).

x. **Collaboration and partnerships**: Achieving zero waste requires collaboration and partnerships between various stakeholders, including governments, businesses, non-governmental organizations, and communities. By working together, different sectors can share knowledge, resources, and best practices to advance zero waste initiatives (Pires & Martinho, 2019).

xi. **Continuous improvement and innovation**: Zero waste management is an evolving process that requires continuous improvement and innovation. As technologies and practices advance, there are always opportunities to enhance waste management systems and achieve higher levels of waste diversion and resource recovery (Bertanza et al., 2018; Haapala et al., 2013).

By embracing these key concepts and principles, zero waste management presents a transformative vision for a more sustainable and circular future. It is a collective effort that involves the commitment of individuals, businesses, policymakers, and communities to reshape waste management practices and create a world where waste is minimized, resources are conserved, and environmental impacts are reduced.

5 5Rs of Zero Waste Management

The 5Rs of zero waste management are a group of guiding principles that emphasize waste prevention and reduction upfront. It aims to reduce the amount of waste produced and advance a more sustainable method of resource management (Tang et al., 2022). These guidelines serve as the basis for zero waste practises and offer a framework for people, organizations, and communities to embrace more ethical waste management practises (Abbas et al., 2019; Franco-García et al., 2019). The 5R's are:

i. **Refuse**: Refusing what is unnecessary is the first and most important step in zero waste management. This entails paying attention to the goods we use and the waste they produce. We may greatly minimize waste at the source by saying "no" to single-use and throwaway goods, superfluous packaging, and non-recyclable materials. Rejecting things that are not necessary or do not support our sustainability ideals reduces the amount of trash produced overall (Faibil et al., 2023; Peng et al., 2018).

ii. **Reduce**: It focuses on reducing material and product use. We may reduce the amount of trash created by being conscious of our shopping behaviour and choosing items with little packaging, robust design, and a longer lifespan. Consumption reduction reduces waste while also conserving energy, raw materials, and other production-related resources (Lange, 2021; Masud et al., 2019).
iii. **Reuse**: A crucial component of zero waste management is reuse of materials wherever possible. Instead of throwing things away after a single usage, we should look for methods to make them last longer. This may be accomplished by giving goods a new life through repair, renovation, or repurposing. Reusable items like water bottles, bags, and containers serve to lessen the demand for disposable alternatives and cut down on waste production (Eriksen et al., 2019; Meidiana et al., 2022; Silva et al., 2017).
iv. **Recycle**: Recycling is the act of turning garbage into new goods or materials in order to prevent it from going to a landfill or being burned. Even while recycling is a crucial part of waste management, it should only be used as a last resort if the first three Rs have been followed. Recycling materials must be properly sorted and separated in order to be processed and reused in the production of new goods (Larrain et al., 2022; Xue et al., 2013).
v. **Repurpose**: Repurposing or upcycling items that may no longer serve their original purpose is the fifth R in zero waste management. We can come up with inventive methods to give things or materials new uses rather than throwing them away. Repurposing objects encourages resourcefulness and creativity in addition to reducing waste (Agarwal & Agarwal, 2021; Flowers & Linderman, 2003) (Fig. 2).

6 Concept of Waste Hierarchy

Waste hierarchy is a key and frequently used concept that offers crucial direction for environmentally friendly waste management techniques. It describes a methodical process to rank waste treatment choices according to their sustainability and adverse effects on the environment. The waste hierarchy is arranged with the most desirable and eco-friendly practices at the top and the least appealing possibilities at the bottom (Fig. 3).

The overarching concept of the waste hierarchy is to "avoid and reduce waste". This level emphasizes how crucial it is to stop waste production at the source and reduce the quantity of waste created. Adopting proactive methods and sustainable practises that lower total demand for raw materials, energy, and resources is the objective here. Designing products with minimal packaging, encouraging sensible consumption patterns, and pressuring firms to use eco-friendly manufacturing techniques are all examples of waste avoidance measures. Societies may greatly reduce the demand for waste management and the accompanying environmental responsibilities by concentrating on trash avoidance and reduction (Gutberlet, 2015; Lesar et al.,

Fig. 2 5Rs of zero waste management

Fig. 3 Concept of waste hierarchy in zero waste management

2018). As we ascend the waste hierarchy, we come across the idea of "reuse waste". This level emphasizes the value of repurposing goods and resources, prolonging their useful lives, and minimizing the demand for new product development. Reuse projects entail restoring, repairing, or reusing objects to keep them from ending up in the trash. Reusing more minimizes not just the amount of trash that has to be disposed off but also the usage of precious resources and greenhouse gas emissions that come from producing new goods (Anawar et al., 2019; Mahongnao et al., 2023). The waste hierarchy's third level is "recycle waste". Recycling is essential to waste management since it involves gathering, processing, and reprocessing resources to make new goods. Recycling relieves strain on natural ecosystems by converting waste materials into useful resources. It also conserves energy and raw materials. Recycling also prevents garbage from going to landfills, which reduces the environmental impact of waste disposal and helps to promote a more sustainable and circular economy (Park, 2021; Tsai et al., 2013). The next step in the hierarchy is "recover energy", which focuses on using some waste materials' potential for energy. By turning non-recyclable garbage into useable energy sources through energy recovery techniques like waste-to-energy incineration, we can lessen our dependency on fossil fuels and reduce greenhouse gas emissions. Energy recovery supports waste management initiatives, but it must be careful not to undermine attempts to reduce trash or recycle (Mancini et al., 2019; Quicker et al., 2020). The waste hierarchy's fifth level is "treat waste". The recovery of valuable materials from organic waste is emphasized at this stage. Anaerobic digestion and composting are two examples of treatment processes that turn organic waste into valuable resources like compost that is rich in nutrients and biogas. In addition to lowering greenhouse gas emissions from landfills, these procedures offer a sustainable option for handling organic waste (Shukla & Khan, 2022). The final step in the waste hierarchy is "dispose of waste". Landfilling is a disposal strategy that is least desired and should only be used in cases where other waste management techniques are impractical. Landfills may have a big influence on the ecosystem, contaminating the soil and water, emitting greenhouse gases, and causing aesthetic blight. According to Abbas et al. (2019) and Goriaeva et al. (2000), the waste hierarchy seeks to reduce dependency on disposal techniques and place an emphasis on sustainable waste management solutions. Individuals, businesses, and governments may manage waste more sustainably by adhering to the waste hierarchy. Prioritizing waste avoidance, reuse, recycling, and resource recovery helps create a circular economy where resources are saved and waste production is reduced, which in turn minimizes environmental consequences. The trash hierarchy supports the objective of building a greener and more resilient future by directing us towards a more sustainable and responsible approach to waste management.

7 Innovative Technologies Driving Zero Waste Management

In order to achieve zero waste goals, technological advancements are especially important in influencing the landscape of waste management practises. In order to maximize resource recovery, lessen environmental effect, and promote sustainable waste management practises, the integration of cutting-edge technology is more important as the world's garbage output rises. We examine a variety of cutting-edge technologies in this part that have been developed to aid in the creation of zero waste management systems. These developments include waste-to-energy options, sophisticated recycling methods, intelligent waste management systems, and the incorporation of blockchain and artificial intelligence. The path to a world with zero waste is made more attainable and revolutionary by embracing these technical advancements.

i. **Waste-to-energy (WtE) technologies**: The goal of waste-to-energy technology is to transform non-recyclable garbage into usable energy sources, such as fuel, heat, or electricity (Mancini et al., 2019). There are various ways to turn garbage into energy, including pyrolysis, gasification, and incineration:

   - **Incineration**: This process involves burning waste at high temperatures in controlled environments. The heat generated during incineration can be used to produce steam, which drives turbines to generate electricity. Incineration significantly reduces the volume of waste and can be an effective solution for handling non-recyclable materials (Quicker et al., 2020).
   - **Gasification and pyrolysis**: Thermal processes called gasification and pyrolysis turn organic waste into synthetic gas (syngas) and charcoal, respectively. While biochar may be used as a soil improvement in agriculture, syngas can be utilized as a fuel for power generation or other industrial purposes (Mancini et al., 2019).

     WtE technologies pose questions about emissions and air pollution even though they can assist to lessen the environmental effects of waste disposal and offer a source of renewable energy. The environmental sustainability of WtE technologies depends on well-planned and run facilities with strong emission control systems.

ii. **Advanced recycling methods**: The goal of innovations in material recycling is to recover valuable resources from difficult-to-recycle complex items and materials. For instance, valuable metals like gold and palladium are recovered from discarded devices through electronic waste (e-waste) recycling technology. Furthermore, improvements in textile recycling allow for the extraction of fibres from used textiles in order to produce new textiles. Modern recycling methods put a strong emphasis on enhancing the efficacy and efficiency of recycling procedures, which results in better rates of material recovery and less trash production. Here are a few of them:

- **Mechanical-biological treatment (MBT)**: To separate recyclables from mixed garbage, MBT combines mechanical sorting and biological processing. The procedure entails shredding the trash to mechanically separate recyclables, followed by biological treatment, such as composting or anaerobic digestion, for the residual organic fraction (Ameli et al., 2019; Larrain et al., 2022).
- **Chemical recycling**: Recycling of feedstock, commonly referred to as chemical recycling, employs chemical procedures to disassemble plastic waste into its monomers, or fundamental components. Closing the loop and lowering the need for virgin plastics is possible by using these monomers to create new plastics (Lai et al., 2022; Park, 2021; Tsai et al., 2013).
- **Plasma gasification**: Plasma gasification is an advanced thermal conversion technology that uses high-temperature plasma to convert waste into a syngas. The syngas can be used for energy production, and the process can handle a wide range of waste materials, including hazardous waste.

Advanced recycling techniques play a crucial role in diverting valuable resources from landfills and promoting a more circular economy where waste is viewed as a resource rather than a burden.

iii. **Smart waste management systems**: More effective garbage collection and processing are made possible by the use of smart waste management systems, which also promote more environmentally friendly waste management techniques. Technology and data analytics are used by smart waste management systems to improve garbage collection, transportation, and processing:

- **Sensor-based waste sorting**: Different forms of waste may be automatically identified and sorted using sensors that are mounted in trash cans or at waste sorting facilities. Due to this technology, recycling procedures are more effective and recyclable materials are less likely to be contaminated (Park, 2021; Tsai et al., 2013).
- **Route optimization**: The routes garbage trucks use to gather waste are optimized using sophisticated algorithms that analyse data on waste generating trends. As a consequence, waste management services use less fuel, emit fewer pollutants, and incur less expense (Lahane & Kant, 2022; Quicker et al., 2020).
- **Internet of things (IoT) integration**: Internet of things (IoT) integration: IoT gadgets may be used to track the amount of waste in bins, allowing prompt collections and avoiding overflow. Additionally, real-time monitoring of waste management procedures is made possible by IoT integration, which enables the detection and correction of inefficiencies (Ameli et al., 2019; Lange, 2021).

iv. **Biological nutrient recovery (BNR)**: BNR focuses on removing useful nutrients from organic waste and wastewater, such as phosphate and nitrogen. These nutrients can be recovered and reused, which eliminates the need for synthetic

fertilizers and closes the nutrient loop. They are crucial for agricultural fertilizers. In addition to recovering nutrients, BNR technologies including struvite precipitation, ammonia recovery, and anaerobic digestion also generate biogas, a sustainable energy source (Lahane & Kant, 2022; Quicker et al., 2020).

v. **Zero waste manufacturing and design**: Optimizing product design to reduce waste generation during production and throughout the product's life cycle is the main goal of zero waste manufacturing and design practices. Utilizing eco-friendly materials, minimizing packaging, creating goods that can be disassembled, and applying closed-loop manufacturing techniques are all part of this. Industries may transition to zero waste production and sustainable consumption habits by using circular design concepts (Larrain et al., 2022; Lesar et al., 2018).

vi. **Distributed waste management solutions**: Smaller-scale waste treatment systems are placed closer to the point of waste creation as part of decentralized waste management solutions. Examples include home composting systems, neighbourhood recycling facilities, and anaerobic digesters for the disposal of organic waste. According to Agarwal and Agarwal (2021) and Mahongnao et al. (2023), decentralization can lower transportation costs, promote community engagement, and open up prospects for the recovery of local resources.

vii. **Artificial intelligence (AI) and machine learning**: To enhance workflows and decision-making, waste management operations are increasingly utilizing AI and machine learning technologies. Large volumes of data can be analysed by these technologies to forecast trash creation trends, improve sorting procedures, and spot possibilities for waste reduction. In addition to encouraging correct garbage separation, AI-driven smart bins can also boost recycling practises amongst the general population (Ameli et al., 2019; Lange, 2021).

viii. **Blockchain technology**: It is being investigated as a way to improve traceability and transparency in garbage management. It may be used to monitor waste streams, confirm recycling and disposal procedures, and make sure waste rules are being followed. Blockchain can promote a more effective and responsible waste management ecosystem and assist stakeholders develop confidence in one another (Bolton & Rousta, 2019; Yang et al., 2023).

ix. **Efficient product packaging**: Innovative packaging techniques seek to minimize waste production, especially in the consumer products industry. This includes supporting reusable packaging models, using compostable or biodegradable packaging materials, and designing packaging that uses as little material as possible (Meidiana et al., 2022; Park, 2021) (Fig. 4).

The path to zero waste is made more realistic and efficient by combining these technological advancements with current waste management practises and legislation. However, it is critical to understand that technology cannot reach zero waste targets on its own; it must be supported by robust regulatory frameworks, widespread public involvement, and a change in perspective towards the circular economy. For the subject of zero waste management to advance, ongoing research, cooperation amongst many stakeholders and constant technology advancement is essential.

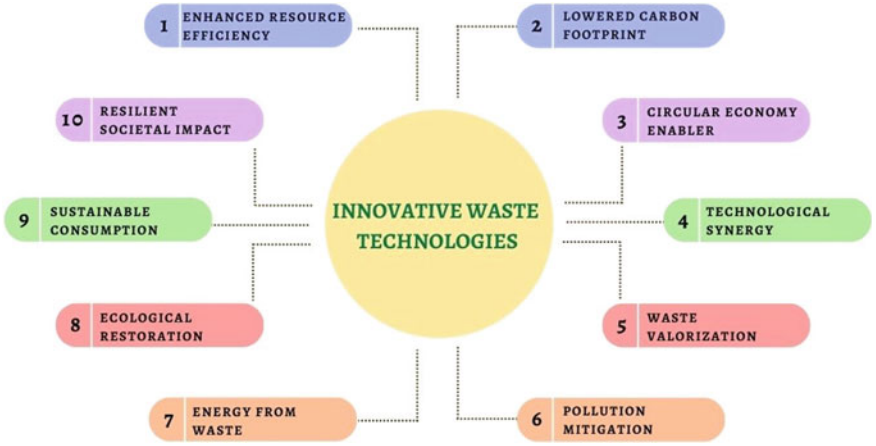

Fig. 4 Advantages of implementing innovative technologies for zero waste management

8 Policy and Legislative Framework for Zero Waste Management

A robust policy and legal framework that offers a clear roadmap, defines goals, and develops laws to direct waste management practises is necessary for the effective implementation of zero waste management. This framework is essential for encouraging sustainable practises, changing behaviour, and fostering an environment that supports resource recovery and waste reduction (Quicker et al., 2020; Rios et al., 2019). The main components of the policy and legal framework for zero waste management are explained in detail below:

i. **Waste management guidelines**: National waste management plans have been formed by several nations, outlining their vision and objectives for resource recovery and waste management. Specific goals for trash diversion, recycling rates, and landfill reduction are frequently included in these programmes. National waste management regulations set the foundation for regional and local implementation of zero waste projects and offer a strategic direction (Haapala et al., 2013; Zhang et al., 2022).
ii. **Waste hierarchy integration**: The inclusion of the waste hierarchy is a crucial component of the policy framework. The waste hierarchy places waste avoidance and reduction at the top of the list, followed by reuse, recycling, energy recovery, and disposal in order of environmental sustainability. Governments emphasize the value of resource recovery and waste reduction by incorporating the waste hierarchy into waste management policy (Faibil et al., 2023; Quicker et al., 2020).
iii. **Extended producer responsibility (EPR)**: Producers are held responsible for the environmental effect of their goods throughout their lifecycles, including the management of post-consumer waste, under the crucial policy approach

known as environmental product responsibility (EPR). Manufacturers are encouraged to build items that are simpler to recycle, repair, or reuse thanks to EPR rules. Additionally, it encourages the development of systems for the collecting and recycling of certain goods and materials, such as packaging, electronics, and batteries (Peng et al., 2018; Portugaise et al., 2023; Tsai et al., 2013).

iv. **Waste collection and separation arrangements**: The policy and regulatory framework must include efficient garbage collection and separation systems. To guarantee that distinct waste streams, such as recyclables, organic garbage, and non-recyclables, are collected separately, governments must enact regulations that encourage source separation at homes, companies, and enterprises. As a result, recycling and resource recovery may be done effectively (Park, 2021; Shukhla & Khan, 2022).

v. **Fixed recycling programmes**: Numerous jurisdictions have put in place obligatory recycling programmes that mandate that companies and households separate recyclables from the waste stream. These initiatives set recycling goals and may apply sanctions for failure to meet them. Governments might promote more involvement and raise recycling rates by making recycling mandatory (Tandon, 2020; Zaman & Ahsan, 2019).

vi. **Monetary enticements and provision**: Financial incentives can be included into the policy framework to promote recycling and waste minimization. For organizations and communities that make investments in waste reduction infrastructure and recycling facilities, these incentives may take the form of grants, subsidies, tax credits, or rebates. The market for recycled materials can also be developed with financial assistance.

vii. **Guidelines on landfilling and incineration**: Policies might establish stringent rules and charge higher costs for waste disposal in an effort to deter the dumping of garbage in landfills and incinerator plants. By creating financial disincentives for disposing of garbage in landfills or incinerators, these policies promote resource recovery and waste reduction (Zlamparet et al., 2018).

viii. **Civic responsiveness and training activities**: There may be provisions in the policy framework for public awareness and education efforts. These campaigns seek to educate the public on the value of recycling, waste reduction, and good waste management techniques. Public education can encourage behavioural changes and boost involvement in garbage reduction initiatives (Portugaise et al., 2023).

ix. **Scrutinizing and reporting means**: Governments can set up reporting and monitoring systems to keep tabs on the development of zero waste objectives. In order to evaluate the success of policies and pinpoint areas for improvement, regular data collection and reporting on trash generation, recycling rates, and landfill diversion are necessary (Abbas et al., 2019; Bertanza et al., 2018).

x. **Collaboration and stakeholder participation**: Collaboration between governmental bodies, corporations, non-governmental organizations, communities, and other stakeholders is essential for the achievement of zero waste management. To progress zero waste projects, the policy framework should

promote stakeholder involvement, public-private collaborations, and knowledge exchange (Pires & Martinho, 2019).

xi. **Novelty and exploration provision**: Policies can encourage the development of new waste management techniques and technologies. Governments may encourage technical breakthroughs that improve trash diversion, recycling effectiveness, and resource recovery by investing in research and development (Tandon, 2020).

The basis of effective zero waste management is a strong policy and legal framework. It offers the required instructions, rewards, and rules to encourage resource recovery, waste reduction, and environmentally friendly waste management techniques. Governments may strive towards attaining their zero waste objectives and promoting a more sustainable future for the world when these efforts are backed by comprehensive legislation.

9 Social and Behavioural Aspects of Zero Waste Management

Initiatives for zero waste management are successfully implemented when social and behavioural factors are taken into account. These factors include people's attitudes, beliefs, values, and behaviours towards waste management practises in communities and organizations. Promoting waste reduction, recycling, and sustainable consumption habits requires an understanding of and attention to social and behavioural variables (Silva et al., 2017; Yang, 2022). As it relates to the social and behavioural components of zero waste management, the following major considerations should be noted:

i. **Public education and awareness**: Promoting public support and engagement in zero waste management requires increasing public understanding of its significance. People can be made aware of the negative effects that trash has on the environment, the advantages of recycling and composting, and the necessity of reducing waste at the source through educational programmes. People are more likely to adopt sustainable waste management practises when they are given knowledge and encouraged to feel responsible (Tang et al., 2022; Tsai et al., 2013).

ii. **Community involvement**: Successfully implementing zero waste projects depends on community involvement. Participation in the community promotes communication of thoughts, issues, and suggestions, fostering a sense of ownership and group accountability. Communities can collaborate to identify problems with waste management, provide solutions, and put into action programmes that are suited to their unique requirements and preferences (Faibil et al., 2023; Polettini, 2012).