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# Recent Trends in Management and Utilization of Industrial Sludge

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*This book;*
*Dedicated to my late Grandparents for their enduring legacy and the values they instilled in me and to my family for their abundant support, patience, understanding, love, encouragement, blessings, and ongoing education have been the cornerstone of this endeavor. Without the unwavering support of my family, this book would not have been possible.—**Vineet Kumar***

*Dedicated to my family, with special acknowledgment to my wife. Without her unwavering support, this project would not have been possible.—**Sartaj Ahmad Bhat***

*Dedicated to my family members and colleagues*
*for their enduring patience and understanding, providing me with the*
*time and inspiration needed for research and editing.—**Pradeep Verma***

*Dedicated to our students, teachers, and mentors, from whom I*
*continue to learn and my family for their unwavering support, blessings,*
*motivation, and love.—**Sunil Kumar***

# Preface

In today's industrial landscape, sustainability is no longer just a buzzword; it is a fundamental imperative. The responsible management and utilization of industrial sludge represent a critical aspect of this journey toward a more sustainable and environmentally conscious future. The book you hold in your hands, *Recent Trends in Management and Utilization of Industrial Sludge*, delves into this often-overlooked facet of industrial processes and waste management.

Industrial sludge, a byproduct of various manufacturing and industrial processes, has traditionally been viewed as a challenge to be managed and disposed of. However, as our understanding of resource conservation and circular economy principles has evolved, so too has our perspective on this complex material. Industrial sludge contains valuable resources that, if harnessed effectively, can not only reduce environmental impact but also yield economic and societal benefits.

This book brings together the collective wisdom of experts, researchers, and practitioners who have dedicated their efforts to exploring innovative ways to manage and utilize industrial sludge. The chapters within these pages cover a wide spectrum of topics, including sludge characterization, treatment technologies, sustainable disposal, and transformative approaches that turn waste into valuable resources. By doing so, this volume contributes to a growing body of knowledge that can reshape our approach to industrial sludge management.

Chapter 1 highlight overcoming obstacles in industrial sludge management through the implementation of diverse solutions. The chapter concludes with a discussion on adopting futuristic trends and technologies, aiming to strike a balance between the economy and the environment, especially when pursuing sustainable development as a primary objective.

Chapter 2 offers a comprehensive characterization of tannery sludge, including basic data such as dry solids, volatile solids, and humidity. The chapter also engages in a discussion of alternative sustainable sludge control models tailored to the specific nature of tannery sludge. Additionally, it highlights the critical importance of selecting appropriate pre-thickening and dewatering/drying equipment in establishing and implementing a sustainable tannery sludge management model.

Chapter 3 provides insights into different strategies employed in the anaerobic digestion of petroleum refinery sludge, including co-digestion, bioaugmentation, and other approaches, evaluating their suitability under various conditions. The chapter also places a particular emphasis on achieving the complete mitigation of petroleum refinery sludge, with a focused discussion on the recovery of biogas.

Chapter 4 offers an overview of the principles and potential benefits of hydrothermal carbonization (HTC) technology when applied to industrial sludge treatment. It delves into the effects of key process parameters on HTC performance, including pressure, temperature, residence time, and feedstock characteristics. The chapter suggests that HTC technology provides a sustainable and efficient method for the treatment and management of industrial waste.

Chapter 5 delivers a comprehensive review of vermistabilization for various industrial wastes, exploring the degradation pathways facilitated by earthworms. The chapter also investigates the effects of various waste-derived biochars as amendments and identifies potential earthworms used in the process, with a special emphasis on the transformation pathway. Additionally, the chapter outlines the future potential for commercializing vermicompost derived from industrial waste using pollutant-loaded biochar.

Chapter 6 offers an overview of recent trends and developments in microbial fuel cells (MFCs), a promising technology for sustainable electricity generation by harnessing microbial metabolic activity to convert organic matter into electrical energy. The chapter underscores that industrial wastewater sludge serves as a rich source of organic matter for MFC feedstock. It reviews the current state of research on optimizing MFC materials production, considering factors like sludge type, electrode material, and operating conditions.

Chapter 7 comprehensively covers various types and sources of industrial sludge, along with the techniques used to treat and synthesize industrial sludge-Based adsorbents (ISBAs). The chapter also discusses parameters like pH, adsorption time, adsorbent dose amount, and temperature that influence the adsorption capacity of ISBAs to absorb pollutants. Furthermore, the application of ISBDs for reclaiming organic compounds, heavy metals, and other pollutants is explored.

Chapter 8 explores the dual environmental and economic advantages of recycling and reusing industrial sludge in construction. This approach not only ensures sustainable management of industrial waste but also alleviates the demand for raw materials in the construction industry.

Chapter 9 focuses on the potential use of poplars in the phytoremediation of polluted sites. This chapter explores the effectiveness of utilizing waste sludge in combination with willows for phytoremediation purposes.

Chapter 10 highlights various techniques for extracting enzymes, such as protease, alkaline phosphatase, lipase, and amylase, from sludge. It covers the types and applications of these enzymes across different industries. The chapter then focuses on the disruption of activated sludge flocs containing crude enzymes, explaining several physical and chemical disruption methods. Subsequently, it outlines the purification of crude enzymes through centrifugation, followed by the steps of enzyme immobilization to enhance their application.

Chapter 11 focuses the formation, processing, and pretreatment approaches of industrial sludge, examining its utilization in agriculture. The chapter explores the use of sludge in the agricultural sector, discussing their respective positive and negative impacts. It concludes with a perspective on the application of industrial sludge in agriculture, shedding light on the challenges to its adoption and the opportunities, particularly in the developing and underdeveloped world.

Chapter 12 offers a comprehensive explanation of the origins of biodiesel, its manufacturing methodologies, and advancements in the biodiesel industry. The chapter outlines the challenges associated with biodiesel production, specifically focusing on the production of biodiesel from industrial sludge. It also sheds light on future perspectives, exploring the development of novel techniques to increase biodiesel production.

Chapter 13 offers a substantial contribution to the fields of waste management and sustainable agriculture by showcasing the innovative and eco-friendly possibilities offered by vermicomposting techniques for resource recovery and environmental enhancement.

As editors, our aspiration for this book is to serve as a comprehensive resource for professionals, researchers, policymakers, and students interested in the sustainable management of industrial sludge. We hope that the insights shared within these chapters will spark new ideas, encourage interdisciplinary collaboration, and drive the adoption of environmentally responsible practices in industries worldwide.

In conclusion, we invite readers to embark on a journey through the pages of *Recent Trends in Management and Utilization of Industrial Sludge*. We believe that the innovative approaches and solutions presented here have the potential to redefine the way we view industrial sludge, transforming it from a challenge into an opportunity for a more sustainable future.

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# Acknowledgments

The development of this book, *Recent Trends in Management and Utilization of Industrial Sludge*, has been a collaborative effort that would not have been possible without the support and contributions of numerous individuals and organizations. We extend our heartfelt gratitude to all those who have played a pivotal role in bringing this project to fruition.

First and foremost, we would like to express our deepest appreciation to the authors of the various chapters who have contributed their expertise and valuable research to make this book a reality. Your dedication to researching, writing, and sharing your expertise has been instrumental in shaping this book and advancing the field of industrial sludge management and utilization. Their contributions have made this book the comprehensive and informative resource that it is. The commitment of contributors to sustainability and advancing the field of solid sludge management are truly commendable.

We also wish to acknowledge the reviewers who generously offered their time and expertise to ensure the quality and rigor of the content presented in this volume. Your insightful feedback and guidance have been invaluable in maintaining the academic excellence of this publication.

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Our gratitude extends to the team at Springer Nature, New York, USA, especially the editorial and production staff, for their professionalism, guidance, and support throughout the publishing process.

We would like to express our sincere gratitude to all of the people who have helped us to complete this book.

Lastly, we acknowledge the unwavering support of our families and friends who have stood by us during the journey of editing this book.

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# Chapter 1
# Fundamentals of Industrial Sludge: Trends and Challenges

**Maryam Eqan, Junfeng Wan, and Yixin Yan**

## 1 Introduction

### 1.1 Definition of Industrial Sludge

Industrial sludge denotes a semi-solid or solid residue formed during an industrial process as a by-product (Philipp & Hoelzle, 2014). It is classically composed of a multi-faceted mixture of inorganic and organic substances, water, and other contaminants (Sathya et al., 2022). According to Shankar et al. (2021), industrial sludge is generated after the sedimentation and filtration of liquid waste material produced from industrial operations, which ensures the separation of solids from the liquid phase. See industrial sludge in the treatment plant in Fig. 1.1.

### 1.2 Characteristics of Industrial Sludge

Proper understanding and managing industrial sludge entails basic familiarity with specific vital characteristics (Kesari et al., 2021). The type of industry, involved processes, and sludge configuration give a specific characteristic to sludge (Kwarciak-Kozłowska & Gałwa-Widera, 2023). The following are some common attributes of industrial sludge:

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**Fig. 1.1** Industrial sludge

### 1.2.1 Physical State

Industrial sludge can be of several physical states, from high moisture-containing liquid slurry to lower water-containing solid and semi-solid matter (Wiśniowska et al., 2019). The consistency and viscosity of the sludge can differ extensively, distressing its management and treatment methods (Hong et al., 2018).

### 1.2.2 Moisture Content

Sludge classically comprises a substantial quantity of water, leading to its mass and volume (Nielsen, 2008). The moisture level can influence the industrial processes and efficacy of utilised dewatering and drying techniques (Bhattacharya, 2023). According to Stewart (2017), the high moisture content in industrial sludge necessitates supplementary treatment measures to ensure efficient disposal.

### 1.2.3 Chemical Composition

According to Thomas and Thomas (2022), industrial sludge is composed of a diverse amalgamation of both organic and inorganic compounds encompassing a wide range of pollutants, including oils, greases, solvents, insecticides, harmful waste substances, heavy metals, salts, minerals, and trace metals from industrial procedures (Chan et al., 2022; Shumbula et al., 2022). The chemical makeup is contingent upon various variables, such as type of industry, raw material employed, and procedure involved (Sasidharan et al., 2011).

### 1.2.4 pH

pH level of industrial sludge exhibits variability, comprising both acidic and alkaline circumstances, relying on the particular industrial procedures and involved components (Kokina et al., 2022). The stability and reactivity of sludge can be impacted by pH levels, which subsequently affect the choice of treatment procedures (Shameem & Sabumon, 2023).

### 1.2.5 Toxicity

Heavy metals (lead, mercury, cadmium, etc.), organic pollutants (polychlorinated biphenyls (PCBs), dioxins, etc.), and other hazardous compounds might be present in industrial sludge (Kumar et al., 2022). These toxic substances can result in serious environmental and health risks without proper management and treatment of these toxic substances (Jaishankar et al., 2014).

### 1.2.6 Odour

Due to the decomposition of organic matter, the presence of sulphur compounds, or the proliferation of anaerobic bacteria, particular kinds of industrial sludge might produce odours (Han et al., 2020). Considering workers' safety, public opinion, and general environmental impact, the odour can be of great concern (Guadalupe-Fernandez et al., 2021).

### 1.2.7 Settling and Separation Properties

Frequently, industrial sludge contains solid particles that can settle due to gravity over time (Singh et al., 2022a, b). Recognition of the settling features of the sludge is crucial for designing efficient sedimentation or clarification procedures during treatment (Hou et al., 2021).

### 1.2.8 Biological Activity

According to its chemical makeup and moisture level, industrial sludge may sustain microbial growth and biological activity (Roy & Saha, 2021). These microorganisms may add to the digestion of organic matter, resulting in the production of gases, heat, and modifications to the chemical and physical properties of the sediment (Soni & Devi, 2022)

## 1.3 Importance of Understanding Industrial Sludge Management

Understanding industrial sludge management is of paramount importance due to several reasons:

### 1.3.1 Environmental Protection

If not correctly managed, industrial sludge may contain hazardous substances, pollutants, and toxic compounds that pose significant environmental risks (Su et al., 2019). It may pollute soil, surface water, and groundwater, causing degradation of ecosystems and water pollution (Singh et al., 2022a, b). Recognising sludge management facilitates adopting suitable treatment and disposal practices to avoid environmental damage and ensure sustainable environmental stewardship (Kacprzak et al., 2017).

### 1.3.2 Human Health and Safety

Industrial sludge may include chemicals, heavy metals, pathogens, and other hazardous substances that may cause detrimental health consequences (Mitra et al., 2022). Exposure to contaminated sludge or its wrong handling may lead to occupational health risks, poisoning of food sources, and the discharge of hazardous chemicals into the air (Padmanabhan & Barik, 2019). Effective management practices safeguard workers, neighbourhoods, and the public from possible health hazards related to industrial sludge (Obaideen et al., 2022).

### 1.3.3 Regulatory Compliance

Several countries and topographical zones have instigated regulatory frameworks and established criteria for the management, treatment, and exclusion of industrial sludge (Khaliq et al., 2017). Intending to sustain compliance, dodge penalties, and keep social and environmental accountabilities, industries essentially own a broad understanding of the legal and regulatory standards (Habibi & Salam, 2023). Effective administrative practices play a vital part in facilitating industries to realise their regulatory accountabilities and maintain constructive repute.

### 1.3.4 Resource Recovery and Recycling

The existence of valued resources, comprising metals, nutrients, and organic materials, has been witnessed in industrial sludge, henceforth bestowing an opportunity for their retrieval and consequent reusing (Seleiman et al., 2020). The understanding of sludge management enables the employment of resource recovery practices, like anaerobic digestion, composting, or thermal processes, to excerpt valued constituents and curtail waste (Liew et al., 2022). This act brings into line the central beliefs of the circular economy archetype and optimises resource consumption (Morseletto, 2020).

### 1.3.5 Cost Efficiency

According to Zhou et al. (2022), practical sludge management approaches will likely increase monetary profits for numerous industrial sectors. According to Wu et al. (2020), the execution of suitable treatment, dewatering, and disposal methods can efficiently alleviate waste volume, reduce transportation costs, and improve reserve apportionment. Moreover, the reclamation of valued resources from sludge has the probability of vintage financial compensation (Zarei, 2020). The knowledge of the finest management approaches empowers industries to rationalise their processes and achieve cost-effectiveness (Kacprzak et al., 2017).

### 1.3.6 Sustainable Development

Managing industrial sludge is significant in tracking sustainable development goals (Obaideen et al., 2022). Industries make valuable contributions to the general sustainability of their procedures by commissioning environmentally sound practices, improving the consumption of resources, and decreasing their ecological influences. Understanding sludge management is critical for industries to ensure their accomplishments are in harmony with the doctrines of sustainable development; in so doing, the long-term well-being of society, the economy, and the environment is fostered (Sugurbekova et al., 2023).

## 1.4 Case Studies of Industrial Sludge Generation and Management in Various Industries

The current study led by Petrovič et al. (2023) investigates the pyrolysis of pre-treated industrial sewage sludge (SS) derived from the vegetable oil sector. The pre-treatment procedures applied in this study include torrefaction and hydrothermal carbonisation (HTC). Furthermore, the present study examined the effects of substituting water with whey as a process liquid in the hydrothermal carbonisation (HTC) process, specifically focusing on its influence on subsequent pyrolysis. The thermogravimetric behaviour of the samples during pyrolysis was modified by the pre-treatment, leading to the emergence of discernible TG and DTG curves, despite comparable levels of mass loss and peak temperatures. The substitution of water with whey in hydrothermal carbonisation (HTC) demonstrated enhanced fuel characteristics of the resulting hydrochar and exerted a beneficial influence on pyrolysis kinetics. This modification led to the attainment of the maximum higher heating value (HHV) and carbon content. The results of the kinetic and thermodynamic analyses demonstrated that the pre-treated samples displayed higher values in comparison to the untreated stainless steel (SS). Moreover, the torrefied samples exhibited the highest values among all the samples. Furthermore, the process fluids derived from hydrothermal carbonisation (HTC) have demonstrated promising potential for application in anaerobic digestion, owing to their elevated levels of total organic carbon (TOC) and chemical oxygen demand (COD). The limitations of the study encompassed conducting pyrolysis experiments on a small scale and exclusively examining the characteristics of solid products. As a result, it is necessary to conduct more investigations on a bigger scale and analyse the gaseous and liquid phases in order to gain a more comprehensive understanding. However, the results establish a basis for developing waste management approaches within the vegetable oil sector and propose potential areas for further investigation, such as examining the impact of minerals on pyrolysis and optimising process parameters.

In a separate investigation conducted by Akter et al. (2023), significant emphasis was placed on the significance of thermal processing and the characterisation of sludges from Bangladesh's textile and food sectors. The objective of this study was to explore the potential of converting these sludges into biochar as a means of efficiently managing effluent. Despite the scarcity of studies on industrial sludge, it demonstrates considerable promise as a viable source for manufacturing biochar. The present study effectively generated biochar from sludges derived from the food and textile industries, wherein the properties of the biochar were strongly influenced by the temperature at which pyrolysis was conducted. The utilisation of biochar generated from these sludges exhibits the potential to enhance agricultural soil quality, facilitating carbon sequestration and assisting in the management of sludge. However, additional research is required to investigate potential industrial applications (https://www.sciencedirect.com/science/article/pii/S2451904923002160).

Górka et al. (2022) at the Kraków-Płaszów wastewater treatment facility in Poland discovered that the amalgamation of water and sewage sludge brings about improved biogas generation. The employment of anaerobic stabilisation methods on the sludge assortment is directed to enhance efficacy, henceforth leading to amplified biogas production. This study suggests that adding water sludge to sewage management might benefit municipal facility waste management.

According to Urban and Isaac (2018), the water and wastewater treatment plants in the densely populated Campinas metropolitan area encounter difficulties regarding sludge disposal. In order to tackle this matter, a linear optimisation approach based on Geographic Information Systems (GIS) was employed. The investigation revealed potential applications for the sludges, including their utilisation in creating ceramic bricks for water treatment plant sludge and their application in sugarcane crop regions for ethanol generation in the case of wastewater treatment plant sludge. This strategy offered decision-makers significant insights into sustainable sludge management by considering reception capacities and practicality. Moreover, the proposed approach demonstrates adaptability and provides a pragmatic option for enhancing the efficient utilisation of sludge in urban treatment facilities.

# 2 Types of Industrial Sludge

There are several types of industrial sludge based on source and composition. See Fig. 1.2 for a graphical representation of types of sludge.

## 2.1 Types of Industrial Sludge Based on Source

### 2.1.1 Wastewater Treatment Plant Sludge

The term “wastewater treatment plant sludge”, referred to as sewage sludge or wastewater solids, pertains to the leftover substance produced as a by-product of wastewater treatment in sewage treatment facilities (Kumar et al., 2021a; Singh et al., 2023). The sludge is a residual material generated during the wastewater treatment procedure, including solid particles, organic matter, inorganic substances, bacteria, and several other impurities that are effectively eliminated from the wastewater (Kumar et al., 2021b; Saravanan et al., 2021).

The sludge in wastewater treatment facilities has identifiable characteristics (Aziz & Mustafa, 2022). The substance’s makeup encompasses organic matter, biodegradable molecules, and inorganic components, such as minerals and salts (Koul et al., 2022). The moisture content of sludge is typically increased due to its origin from wastewater and the subsequent treatment procedures (Nazari et al., 2018). Furthermore, it is noteworthy to mention that it may contain substantial amounts of essential nutrients, like nitrogen and phosphorus (Kirchmann et al., 2017). However, the existence of sludge also presents notable risks as it has the potential to act as a reservoir for viruses, pathogens, and toxic substances, including heavy metals and persistent organic pollutants (Okoye et al., 2022). The extent of sludge volume and density variations depends on the particular treatment methods utilised, resulting in the release of unpleasant-smelling chemicals (Byliński et al., 2019). A thorough understanding of these characteristics is imperative for the effective execution of sludge management strategies, encompassing appropriate processing, safe disposal, and prospective resource exploitation, all while maintaining environmental conservation and adherence to legal frameworks (Chandra & Kumar, 2017a, b).

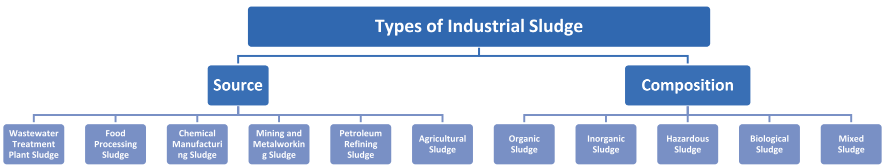


**Fig. 1.2** Types of industrial sludge

### 2.1.2 Food Processing Sludge

The terminology "food processing sludge" pertains to the residual material generated as a secondary output while processing food and beverage products (Despoudi et al., 2021). Insam et al. (2018) posits that the production of this material is a consequence of several food-processing practices, including the processing of fruits and vegetables, meat and poultry, dairy products, grain milling, and beverage manufacturing. Food processing sludge is a composite mixture of organic substances, inorganic compounds, water, and various contaminants that are removed or separated throughout food processing (Mong et al., 2021).

According to Nielsen et al. (2019), the sludge's moisture and nutrient contents differ depending on the processing methods employed. Food waste is frequently present in this context, including various components such as trimmings and expired items. Additionally, the presence of contaminants, such as pesticides and additives, is a common occurrence (Jones et al., 2021). The presence of odours may need actions to control them (Wysocka, 2023). Effective management practices, such as dewatering, stabilisation, and resource recovery, are pivotal in mitigating environmental consequences and optimising sustainability within food processing operations (Shabir et al., 2023).

### 2.1.3 Chemical Manufacturing Sludge

Chemical manufacturing sludge pertains to the residual substance generated as a by-product during manufacturing procedures within the chemical industry. The by-product in question comprises solid particles, chemicals, and various pollutants that undergo separation or removal procedures during chemical production (Yang et al., 2020).

The presence of toxic substances and hazardous materials necessitates the implementation of appropriate protocols for handling and disposal. According to Kocbek et al. (2022), the moisture content of the sludge exhibits variability, and its treatment and disposal procedures are influenced by its physical qualities, including viscosity and density. The presence of contaminants, such as impurities and trace metals, necessitates meticulous management. Stability considerations and adherence to environmental standards cannot be overstated, as they are crucial in light of the possible risks associated with the sludge. Various treatment processes, such as solidification, stabilisation, neutralisation, and burning, are utilised to limit potential hazards and maintain adherence to regulatory requirements in the management of chemical industrial sludge (Kocbek et al., 2022).

### 2.1.4 Mining and Metalworking Sludge

Mining and metalworking sludge is the residual substance of mining and metal processing activities. The by-product in question encompasses solid particles, chemicals, minerals, and various pollutants that undergo separation or extraction procedures in mining and metalworking operations (Wang et al., 2022).

The sludge can potentially contain hazardous substances, such as poisonous compounds, heavy metals, and even radioactive materials, which can pose significant threats to the environment and human health. The material's moisture content, physical characteristics, and mineral makeup exhibit variations contingent upon the operation (Alwaeli et al., 2020). Inadequate handling of sludge has the potential to result in the contamination of land and water sources (Rorat et al., 2019). Hence, it is imperative to comprehend the distinctive attributes of mining and metalworking sludge to effectively apply suitable treatment techniques, including dewatering, solidification, and stabilisation. This understanding is essential for adhering to environmental regulations, aiming to reduce environmental consequences and mitigate potential risks associated with such sludge.

### 2.1.5 Petroleum Refining Sludge

Petroleum refining sludge pertains to the residual or discarded substance that is formed as a by-product during the process of refining crude oil to manufacture diverse petroleum products. The by-product in question comprises solid particles, hydrocarbons, heavy metals, and various pollutants that are amassed due to the refining process (Choudhury et al., 2022).

The sludge has a notable hydrocarbon concentration and a high viscosity level, resulting in a dense and adhesive consistency. In addition, the presence of sulphur compounds and heavy metals has been identified as contributing factors to its poisonous nature (Agoro et al., 2020). The sludge frequently exhibits a notable water content due to using water in refining (Johnson & Affam, 2019). According to Johnson and Affam (2019), inadequate disposal of petroleum refining sludge can result in environmental contamination, presenting hazards to ecosystems and human well-being. Effective management and treatment strategies, such as sedimentation, filtration, and heating processes, are crucial in reducing the environmental consequences and addressing the potentially harmful characteristics of sludge generated from petroleum refining activities.

### 2.1.6 Agricultural Sludge

Agricultural sludge is the organic waste produced by agricultural activities and practices. The by-product in question comprises diverse organic compounds, such as animal manure, crop leftovers, agricultural runoff, and other organic residues derived from farming activities (Sharma & Garg, 2019).

The substance exhibits a high concentration of organic matter and essential nutrients, including nitrogen, phosphorus, and potassium. The moisture content exhibits variability and is crucial in facilitating microbial activity, hence contributing to the decomposition of organic matter (Chen et al., 2022). Nevertheless, it is essential to note that agricultural sludge may also harbour infections, herbicides, and heavy metals, requiring appropriate management strategies to mitigate potential health and environmental hazards. According to Alengebawy et al. (2021), correctly applying this technique can enhance soil structure, fertility, and water-holding capacity. Composting, anaerobic digestion, and nutrient recovery represent prevalent treatment methodologies. The comprehension of the attributes of agricultural sludge facilitates its secure and enduring utilisation within agricultural systems, concurrently fostering the principles of environmental stewardship (Alengebawy et al., 2021).

## 2.2 Types of Industrial Sludge Based on Composition

### 2.2.1 Organic Sludge

The term "organic sludge" pertains to sludge predominantly composed of organic material originating from biological sources, like sewage, food waste, or agricultural wastes (Clapp et al., 1986). Typically, it exhibits a high concentration of organic components, encompassing proteins, carbohydrates, and lipids. Organic sludge may arise as a by-product of several activities, such as wastewater treatment, composting operations, or organic waste management (Chen et al., 2011; Kumar & Thakur, 2020). Preventing odour concerns, facilitating decomposition, and guaranteeing proper disposal or beneficial reuse frequently necessitate implementing suitable treatment and management strategies.

### 2.2.2 Inorganic Sludge

Inorganic sludge mainly consists of inorganic substances, such as minerals, metals, or chemicals (Kumar & Chandra, 2020; Udayanga et al., 2019). It is frequently derived from industrial operations, such as mining, metalworking, or chemical manufacturing. Climate Policy Watcher (2023) states that inorganic sludge may comprise heavy metals, hazardous compounds, or other inorganic pollutants. Consequently, it is imperative to exercise caution while managing, treating, and disposing of such sludge to avert potential environmental contamination.

### 2.2.3 Hazardous Sludge

Hazardous sludge substantially threatens human health and the environment due to its poisonous, combustible, corrosive, or reactive characteristics (Hakiki et al., 2019). The phenomenon might manifest because of many industrial operations, encompassing the manufacture of chemicals, the management of hazardous waste, or the clean-up of contaminated sites. Properly managing hazardous sludge necessitates utilising specialised handling, treatment, and disposal protocols. These procedures must adhere to rigorous rules to safeguard human health and the environment (Kanagamani et al., 2021).