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SUSTAINABLE REUSE AND RECYCLING OF AGRO-INDUSTRIAL EFFLUENT

Edited by ABU ZAHRIM YASER,
PRAMILA TAMUNAIDU AND JUNIDAH LAMAMING

Sustainable Reuse and Recycling of Agro-Industrial Effluent

Combating climate change and securing water for future generations require rethinking waste as opportunity. This book presents a timely and accessible roadmap for transforming agro-industrial effluent from an environmental liability into a suite of value-added, sustainable resources.

At its core, the volume systematically covers the science and technology of effluent valorization: recovering inherent energy for bioenergy, extracting phosphorus for cleaner fertilizer production, and purifying water to standards suitable for irrigation or non-potable reuse. It goes further, detailing the conversion of effluent into biofertilizers, liquid nutrient formulations, and microalgae biomass, and exploring its use as a plant growth stimulant. Each pathway is framed within a circular water economy, emphasizing operational efficiency, alignment with SDG 6, 7, and 12, and the integration of environmental, societal, and economic impact assessments. Practical processing methods, resource recovery strategies, and quality upgrading techniques are presented so that reuse is both technically viable and environmentally responsible.

Original and actionable, this book offers an integrated framework that reframes effluent as a multipurpose resource rather than waste. It demonstrates advantages like phosphorus retrieval without relying on sewage sludge, and provides clear guidance for researchers, engineers, technologists, policymakers, and agro-industry stakeholders seeking to implement sustainable effluent management at scale.

Salient features to stress in promotion include:

This book's uniqueness lies in its holistic and practical reframing of agro-industrial effluent, from environmental burden to a diversified resource portfolio. It integrates cutting-edge recovery technologies including energy, nutrients, and biomass with water purification, framed explicitly against global sustainability goals (SDG 6, 7, and 12), and evaluates outcomes across environmental, societal, and economic dimensions. Promotion should stress its interdisciplinary utility (researchers, engineers, industry, policy), its real-world applicability with actionable processing pathways, and its novel comparison of resource recovery strategies within a circular economy paradigm.

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Preface

The accelerating growth of agro-industrial activities, while vital for economic development and food security, presents escalating challenges in the management of effluent and waste streams. In particular, the environmental impact of improperly treated or disposed agro-industrial effluents necessitates urgent, sustainable, and scientifically grounded interventions. This book, *Sustainable Reuse and Recycling of Agro-Industrial Effluent*, aims to serve as a comprehensive reference that addresses these challenges through interdisciplinary perspectives and practical innovations.

This book brings together research and case studies that explore the recovery and reuse of valuable resources from effluents, with a strong emphasis on environmental protection, socioeconomic development, and the transition towards a circular economy. Various chapters investigate the potential of palm oil mill effluent (POME) as a substrate for the production of biogas, the cultivation of microalgae, and the generation of struvite as a slow-release fertilizer, demonstrating a closed-loop system that benefits both industry and the environment.

Technologies such as membrane filtration, constructed wetlands, and aquaponics are explored as viable treatment and reuse strategies. These systems not only reduce the pollutant load in agro-industrial effluents but also enhance water and nutrient recovery, aligning with the principles of the blue–green economic model. In addition, the use of cellulose-based materials from agricultural waste for effluent treatment reflects an innovative and biodegradable alternative to conventional methods.

The book also addresses the complex interactions between agricultural and socioeconomic factors, emphasizing community involvement, policy integration, and economic incentives in achieving sustainable wastewater management. The role of leachate control and nutrient recycling in both rural and industrial contexts is discussed, showcasing scalable models that can be adopted globally.

By compiling advanced research, field applications, and policy insights, this book contributes to a deeper understanding of how agro-industrial effluents can be transformed from environmental burdens into resources of value. It is our hope that this work will inspire further innovation and collaboration among researchers, practitioners, and policymakers striving for a sustainable and resilient agro-industrial future.

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1 Introduction

Junidah Lamaming, Pramila Tamunaidu, and Abu Zahrim Yaser

The agro-industrial sector produces huge amounts of effluent as a result of activities including palm oil milling, rubber processing, dairy production, pulp and paper industry, and fruit canning. Traditionally regarded as waste, these effluents offer major risks to the environment if not appropriately treated, such as water contamination, greenhouse gas emissions, and land degradation (Musa et al., 2019; Zahrim et. al., 2007). However, increasing environmental awareness and the push for circular economy practices have sparked interest in the long-term reuse and recycling of agro-industrial effluents. This approach not only mitigates the environmental effect, but also allows for resource recovery, such as energy, nutrients, and water (Bhatia et al., 2021).

The improper disposal of agro-industrial effluents presents considerable environmental challenges, such as soil degradation, water contamination, and loss of biodiversity. These effluents, rich in organic matter and chemicals, can lead to eutrophication in aquatic systems and disrupt ecological balances (Smith et al.,2023). These effluents frequently contain harmful elements, including heavy metals and emerging contaminants (ECs), which may remain in the environment and infiltrate the food chain. Recent studies have found a diverse range of emerging contaminants in many environmental matrices highlighting the difficulties of addressing such pollutants (Smith et al.,2023; Lee et al., 2024). The existence of these contaminants hinders water reuse initiatives, as traditional treatment methods may inadequately eliminate them, necessitating advanced treatment technology.

To address these challenges, innovative treatment technologies have been developed. Membrane technologies, such as ultrafiltration and nanofiltration, have shown promise in removing contaminants from agro-industrial effluents, enabling water reuse and resource recovery (Zahrim et al., 2011). These systems can remove a wide range of pollutants, enabling water reuse and reducing environmental discharge (Patel et al., 2022). Additionally, the use of magnetic cellulose aerogels has emerged as an effective method for oil spill remediation in effluents, offering a sustainable and biodegradable solution (Kumar & Li, 2021; Muharja et al., 2023). Their high porosity and magnetic properties allow for efficient oil adsorption and easy recovery, offering an eco-friendly alternative to traditional sorbents. Constructed wetlands also provide a cost-effective and environmentally friendly approach for treating agro-industrial wastewater, utilizing natural processes to remove pollutants. They utilize vegetation, soil, and microbial activity to remove contaminants, offering a sustainable and cost-effective treatment method. Their adaptability to various waste types makes them suitable for diverse agro-industrial applications (Thompson et al., 2020).

Beyond treatment, the sustainable reuse of agro-industrial effluents presents opportunities for environmental, agricultural, and socioeconomic benefits (Ahmed & Chen, 2023). For instance, oil palm by-products have been utilized as carrier materials in expanded bed processes to polish palm oil mill effluent (POME), enhancing treatment efficiency (Tan et al., 2022). Additionally, nutrient-dense POME has been investigated as a substrate for increased biogas production via co-digestion methods, aiding in sustainable energy generation and waste minimization (Zhang & Kumar, 2020; Rahman & Singh, 2021). Implementing co-digestion strategies can improve energy recovery from agro-industrial waste streams (Rosly et al., 2024). These methodologies conform to circular economy concepts, converting trash into valuable resources.

Innovative applications of agro-industrial effluents include the cultivation of microalgae for wastewater treatment and resource recovery. Microalgae efficiently eliminate nutrients and pollutants from wastewater while generating biomass suitable for biofuels, animal feed, and bioactive chemicals (Silva & Torres, 2022). Marine microalgae provide a sustainable method for the production of bioactive chemicals for feed and food applications. Cultivating these microalgae using agro-industrial effluents as growth media offers a sustainable production method (Wang & Lee, 2023). Furthermore, the incorporation of effluent reuse in aquaponics systems has been investigated to enhance nutrient recycling and promote sustainable agriculture (Johnson & Patel, 2021). Innovations in system design and effluent treatment are crucial to ensure the safety and efficiency of such integrations. Moreover, chitosan, derived from agro-industrial waste, serves as an eco-friendly agricultural input with biostimulant and antimicrobial properties. Its application can enhance crop growth and resilience, contributing to sustainable farming practices. Developing efficient extraction methods is key to its broader adoption (Fernandez & Kim, 2020).

Recent advancements have demonstrated the potential for converting leachate, biomass waste, and agro-industrial effluents into valuable agricultural inputs. Research indicates that leachate can be converted into liquid organic fertilizers via approaches such as phytoremediation in wetland systems, which stabilize harmful constituents while enhancing the leachate with nutrients advantageous for plant growth (Ugya & Meguellati, 2022). Subcritical water treatment effectively breaks down agricultural biomass

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waste, enabling the efficient extraction of bioactive compounds, nutrients and conversion into valuable products such as organic fertilizers, soil amendments (Asmadi et al., 2023), and animal feed (Huzir et al., 2024). The recovery of struvite, a crystalline compound abundant in phosphorus and nitrogen from agro-industrial wastewater, is acknowledged as an effective method for producing environmentally sustainable fertilizers. Struvite functions as a slow-release fertilizer, improving soil fertility and reducing environmental pollution. These methods are consistent with circular economy principles, converting waste into resources and fostering sustainable agricultural practices.

The application of treated agro-industrial effluents for irrigation has emerged as a sustainable method to improve soil fertility and increase crop productivity (Disciglio et al., 2015). Studies demonstrate that appropriately treated effluents can provide vital inorganic nutrients, such as nitrogen and phosphorus, thereby decreasing dependence on synthetic fertilizers. It is essential to monitor and manage the concentrations of these nutrients to prevent soil contamination and promote optimal plant growth. The implementation of controlled irrigation strategies utilizing nutrient-rich effluents can contribute to sustainable agriculture and resource conservation.

Energy efficiency in wastewater treatment processes is essential for sustainable environmental management. Comparative studies indicate that anaerobic treatment systems typically exhibit lower energy consumption compared to aerobic systems, largely due to the significant energy demands associated with aeration in the latter (Ranieri et al., 2021). Additionally, anaerobic processes yield biogas, which serves as a renewable energy source, reducing operational energy costs and contributing to lower greenhouse gas emissions. Hence, optimizing treatment methods is crucial for improving the sustainability of wastewater management facilities.

The integration of blue-green infrastructure (BGI) with circular economy principles offers a comprehensive strategy for sustainable wastewater management (Perrelet et al., 2024). BGI encompasses natural and semi-natural systems such as wetlands and green roofs, which effectively manage stormwater, enhance water quality, and offer supplementary ecosystem services. The integration of circular economy strategies focused on resource recovery and reuse, including nutrient extraction and water reclamation, can markedly diminish environmental impacts while generating economic opportunities. The implementation of integrated approaches is essential for tackling the multifaceted challenges associated with wastewater management in both urban and agricultural environments (Setiawan et al., 2024).

Sustainable effluent management involves converting waste streams into value-added products such as biogas, biofertilizers, irrigation water, or bio-based chemicals. Technologies like anaerobic digestion, constructed wetlands, membrane filtration, and advanced oxidation processes are increasingly being applied to enhance the reuse potential of these effluents (Yacob et al., 2011; Sharma & Sanghi, 2012). By integrating eco-efficient treatment systems with production processes, industries can reduce their ecological footprint while contributing to sustainable agriculture and rural development. Thus, the reuse and recycling of agro-industrial effluents is not merely an environmental obligation but a strategic opportunity for sustainability, innovation, and economic resilience in agro-based industries.

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7 Sustainable Reuse of Agro-Industrial Effluents

Environmental, Agricultural, and Socioeconomic Perspectives

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INTRODUCTION

The rapid rise of agro-industrial activities has led to the production of harmful effluents containing pollutants that threaten water, soil, and biodiversity. Traditional disposal methods, such as direct discharge and landfilling, have worsened environmental damage and contributed to climate change. Therefore, implementing sustainable effluent management strategies is urgently needed to reduce pollution, conserve resources, and protect ecosystems from long-term harm. This chapter employed a qualitative integrative review of literature from 2010 to 2024, sourced from major academic databases. Relevant studies were categorized into five key themes: environmental impact, plant performance, germination indicators, public health, and economic viability.

This chapter critically examines the opportunities and challenges of reusing agricultural wastewater. While it offers benefits like improved soil fertility and nutrient recycling, concerns include heavy metal buildup, variable crop responses, and community resistance. Advanced membrane filters remove contaminants effectively, but issues like fouling, high costs, and poor durability limit their use. Nature-based options like artificial wetlands face seasonal and maintenance challenges. These obstacles highlight the urgent need for cost-effective, sustainable, and environmentally friendly effluent management solutions (Abideen et al., 2024; Mei et al., 2023; Gupta et al., 2024).

As environmental and resource management concerns rise, agro-industrial effluent reuse and recycling have become viable alternatives to traditional disposal techniques (Ma et al., 2014). By encouraging effective water use, waste reduction, and climate-resilient industrial practices, this strategy supports the Sustainable Development Goals (SDGs) of the UN 2030, especially SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). It could employ effluent reuse, which can convert industrial and agricultural waste into useful resources. Furthermore, it has been demonstrated that the regulated use of treated wastewater in agriculture raises soil fertility, boosts crop yield, and promotes the circular economy, all of which are advantageous to the economy and the environment (Christou et al., 2024; Mora et al., 2022).

Despite growing interest in sustainable effluent reuse, its widespread adoption remains limited due to environmental risks, inconsistent crop responses, public health concerns, and economic uncertainties. A lack of standardized treatment protocols, regulatory frameworks, and cost-benefit analyses further complicates implementation (Haider et al., 2023). Studies show heavy metals can degrade soil fertility (Yin et al., 2020), while long-term reuse may cause salinity buildup. Research on productivity, germination, social acceptance, and feasibility remains fragmented. However, global research, especially from China, and national water security strategies in arid regions highlight growing recognition of effluent reuse as a vital solution (Gallego-Valero et al., 2021).

This section offers a multidisciplinary assessment of agro-industrial effluent reuse by examining plant productivity, germination index, social factors, economic feasibility, and policy innovation. Effluent reuse impacts soil health, water quality, and biodiversity, with bioremediation using microalgae showing promise in reducing nutrient loads (Liberti et al., 2024; Nayana et al., 2024). However, more research is needed to enhance treatment efficiency and ensure long-term ecological balance. Plant productivity and germination index serve as bioindicators of effluent effects; some studies report improved germination, while others note possible physiological stress (Atta et al., 2024; Iqbal et al., 2013).

Social acceptance and public health concerns heavily influence adoption. Despite scientific support for treated effluents, fears over food safety and contamination deter implementation (Shuai et al., 2022; Zheng et al., 2023). Economic viability studies suggest long-term benefits, but high initial costs require government support (Hur et al., 2024; Wang et al., 2019).

Lastly, the advancement of sustainable effluent management depends on technology and policy breakthroughs. Nanomaterials and bio-electrochemical systems (BES) are

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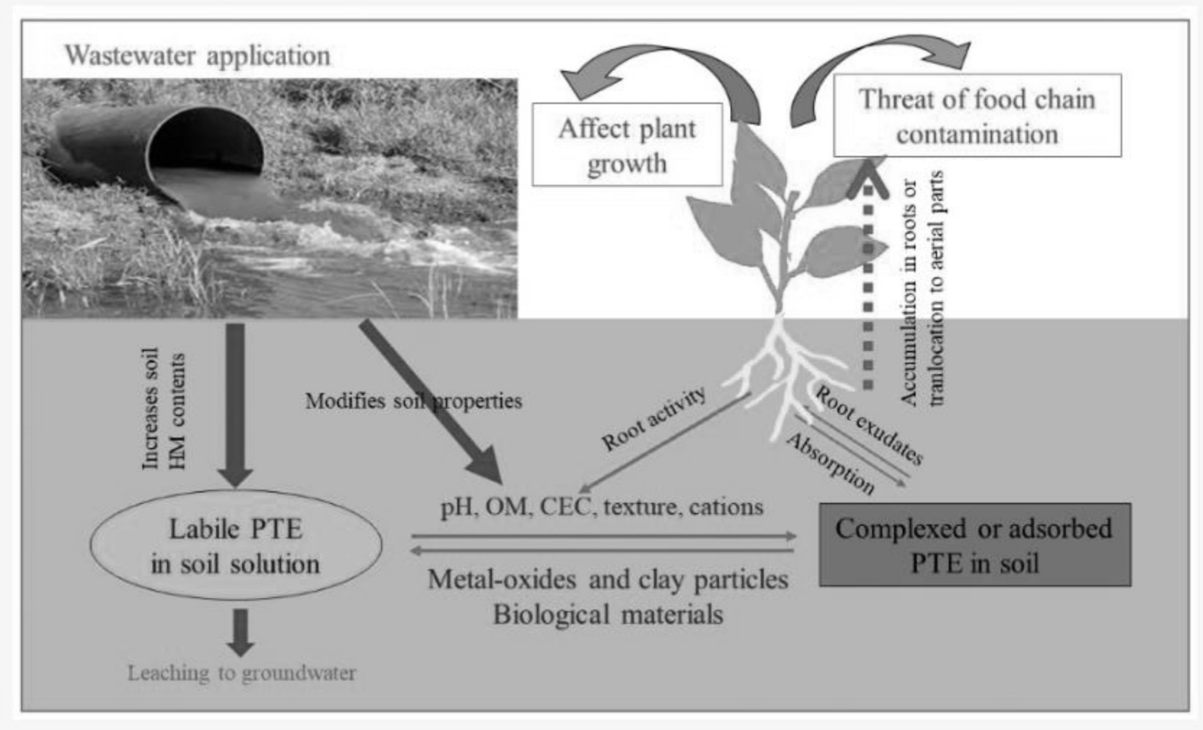

FIGURE 7.1 The potential for wastewater usage to contaminate the environment. Reproduced with permission from Khalid et al. (2018). Copyright, the Creative Commons Attribution (CC BY) license.

examples of emerging technologies that have demonstrated encouraging outcomes in terms of increasing treatment efficiency. However, more investigation is necessary to evaluate their scalability and practicality (Jadhav et al., 2025; Jamil et al., 2022; Yadav et al., 2025). This book chapter seeks to provide readers with a comprehensive grasp of agro-industrial wastewater reuse and its sustainability implications by addressing these factors.

Through the integration of economics, social studies, agronomy, and environmental science, this chapter offers a comprehensive strategy for sustainable effluent reuse. It supports the implementation of environmentally beneficial and financially feasible waste management techniques by providing scientific insights, real-world case studies, and policy suggestions. Researchers, legislators, and business experts looking for long-term solutions for agro-industrial waste management will find great value in the conclusions and debates presented in this chapter.

ENVIRONMENTAL AND AGRICULTURAL IMPACT

Effects of Effluent Reuse on Soil Health, Water Quality, and Biodiversity

Sustainable agro-industrial effluent reuse can enhance soil health and conserve water, but poses serious risks due to heavy metal buildup. While farmers use untreated wastewater to offset shortages and costs, long-term exposure can degrade soil, reduce crop quality, and cause toxic metal accumulation in food, especially in regions like Pakistan, threatening food safety and public health (Amara et al., 2023) (Figure 7.1) (Khalid et al., 2018; Nazli et al., 2020).

Impacts of Effluent Reuse on Soil Quality and Heavy Metal Accumulation

Reusing agro-industrial wastewater can boost soil fertility and irrigation by supplying nutrients and organic matter that enhance microbial activity. However, long-term use raises ecological risks, especially heavy metal accumulation (e.g., Pb, Cr, Cd), which alters soil chemistry and harms microbial diversity (Abideen et al., 2024). While short-term pot and column studies show improved soil health, they may overlook long-term hazards like metal leaching and crop bioaccumulation (Ma et al., 2014). Remediation methods, including bioremediation with rhizobacteria and *Trichoderma* and chemical treatments like gypsum, show promise but depend on site-specific factors and may cause secondary issues (Vivaldi et al., 2022). Sustainable reuse requires long-term soil monitoring, integrated remediation strategies, and multi-season field trials to ensure safe, productive agricultural systems.

Researchers have looked for biological ways to reduce these dangers, concentrating on rhizobacteria that can withstand heavy metals. These helpful microorganisms are essential for controlling the intake of metals, eliminating harmful ions, and promoting plant development by producing phytohormones. This method promotes crop resilience