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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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4 Harnessing Membrane Technologies for Cleaner Agro-Industrial Effluent Management

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INTRODUCTION

Agro-industrial activities play a pivotal role in global food supply chains and economic development (Wang *et al*., 2024). However, these industries contribute significantly to environmental pollution through the generation of agro-industrial effluents. These effluents encompass a wide range of wastewater types, including dairy industry effluents, palm oil mill effluents (POME), sugar mill wastewater, fruit and vegetable processing wastewater, brewery effluents, slaughter wastewater, and starch processing effluents. Each of these wastewater types contains distinct pollutants, such as high organic matter content, polyphenols, fats, proteins, and suspended solids, making them hazardous if discharged untreated. Prominent examples include POME, which has a high biochemical oxygen demand and chemical oxygen demand (COD) (Zainal *et al*., 2017), and dairy industry effluents, which are rich in fats, proteins, and lactose (Fatima *et al*., 2021). Without proper treatment, these pollutants can disrupt ecosystems, cause eutrophication, and pose risks to human health (Porwal *et al*., 2015).

Given the growing environmental changes and increasing regulatory pressures, the need for cleaner and more effective effluent management has never been more critical. Effective treatment not only reduces environmental harm but also supports the transition to sustainable industrial practices. Traditional treatment methods such as sedimentation, biological treatment, and chemical coagulation have been widely adopted. However, these approaches often struggle to address the complexity and persistence of certain pollutants. For instance, conventional biological treatments are inefficient in fully degrading fats, proteins, and lactose, leading to system clogging and incomplete removal of organic matter (Slavov, 2017). Similarly, POME's high oil and grease content can interfere with microbial activity, reducing the efficiency of biological treatment processes (Ilyasu *et al*., 2024). These limitations highlight the need for advanced and innovative approaches.

In recent years, membrane technologies have emerged as a transformative solution in effluent treatment. Processes such as ultrafiltration, nanofiltration, and reverse osmosis have demonstrated high efficiency in removing organic matter, suspended solids, and even trace contaminants. These technologies are valued for their precision, scalability, and potential to recover valuable resources, such as water for reuse and nutrients for agricultural applications. Furthermore, membrane systems can be integrated with other treatment methods, enhancing their efficiency and adaptability across various types of agro-industrial effluents.

Despite these advancements, knowledge gaps remain regarding the optimization, cost effectiveness, and long-term performance of membrane-based treatments for highly complex agro-industrial wastewater. Additionally, fouling and energy consumption pose challenges that limit large-scale adoption. Therefore, this chapter aims to explore the characteristics of agro-industrial effluents, their environmental impact, and the critical role of cleaner technologies, particularly membrane systems in driving sustainable wastewater management. By addressing the limitations of conventional in membrane filtration, this work contributes to the development of more efficient, scalable, and environmentally sustainable wastewater treatment solutions.

MEMBRANE TECHNOLOGIES

Membrane technology has grown in recent years due to its outstanding alignment with sustainable development and process intensification. Moreover, it offers concrete benefits in the production processes, such as significant reduction of equipment size, boosting efficiency, energy savings, reducing capital costs, minimizing environmental impact and increasing safety (Quist-Jensen *et al*., 2015). Basically, a membrane is a barrier which separates two phases from each other by restricting movement of components through it in a selective style (Ezugbe and Rathilal, 2020). Membranes have been in existence since the 18th century. Since then, a lot of improvements have taken place to make membranes better suited for many different applications (Fane *et al*., 2011). Membranes can be categorized as isotropic

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