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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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Pramila Tamunaidu, Malaysia–Japan trained chemical engineer turned educator and researcher at Universiti Teknologi Malaysia, Malaysia, champions circular bioeconomy, zero waste, and zero hunger. With award-winning innovations and Malaysia–Japan collaborations in waste valorization, water treatment, and biofuels, she brings deep expertise and advocacy towards various cradle-to-cradle concepts.

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22 Challenges and Future Perspectives

Pramila Tamunaidu, Junidah Lamaming, and Abu Zahrim Yaser

The book presents a multi-faceted exploration of agro-industrial effluent management through sustainable reuse and recycling. This book represents a transformative approach to turning waste into valuable resources and brought together diverse perspectives and emerging innovations that aim to close the loop in agro-industrial processes, contributing to both environmental preservation and economic sustainability. The chapters collectively demonstrate how agro-industrial effluent management is evolving from a reactive, end-of-pipe treatment approach to a proactive, resource-oriented strategy embedded within circular economy frameworks.

The first three chapters provide a foundational understanding of the challenges associated with agro-industrial effluents. Chapters 1 through 3 lay the groundwork by highlighting the environmental implications of improper disposal of untreated effluents and the challenges posed by emerging contaminants (e.g., pharmaceuticals, microplastics, endocrine disruptors), thus establishing the need for safer and more effective reuse systems or advanced treatment protocols (Kümmerer et al., 2018).

Chapters 4 to 6 focus on technological solutions for effluent treatment. These include the application of membrane technologies, magnetic cellulose aerogels, and constructed wetlands, each offering innovative, cost-effective, and environmentally friendly alternatives for cleaner effluent management.

Chapters 7 to 14 cover resource recovery potentials, forming the core of the book's discussion on circular economy applications. Topics include the use of oil palm by-products in adsorption systems, biogas generation via co-digestion of POME, and the integration of microalgae for both treatment and biomass production. Additionally, there is a strong emphasis on bio-based innovations, including enzyme production, aquaponics, and chitosan-based agricultural inputs, which exemplify closed-loop strategies.

Chapter 15 onward explore the industrial applications and systemic integration of treated agro-industrial effluents. Chapters 15 to 18 emphasize the downstream valorization of treated effluents into high-value products such as liquid fertilizers, struvite, and biostimulants, thereby reinforcing the critical link between waste reuse and sustainable agriculture. Building on these technological pathways, the subsequent chapters (19–21) shift toward broader systemic perspectives, including energy optimization in wastewater treatment, the integration of blue–green economic models, and the financial viability of circular wastewater strategies.

Collectively, these chapters underscore the importance of aligning technological innovations with economic viability and national sustainability agendas, highlighting the multifaceted benefits of integrating effluent reuse within circular and low carbon development frameworks.

TECHNOLOGICAL CONVERGENCE AND INNOVATION TRENDS

The book highlights a clear focus on the convergence of multiple disciplines and technologies to address the multifaceted challenges of agro-industrial effluent management. Hybrid treatment systems such as the integration of membrane filtration with biological digestion have shown enhanced pollutant removal efficiencies while simultaneously reducing sludge generation and energy consumption. These membrane-biological hybrid systems are particularly effective for high-strength wastewaters with complex organic loads.

Advances in material science further support this technological convergence. The application of low-cost, green biosorbents such as magnetic cellulose aerogels and chitosan not only improves adsorption efficiency for contaminants but also ensures biodegradability and scalability in alignment with green chemistry principles. In parallel, the inclusion of microalgae and marine organisms presents new opportunities for integrated nutrient recovery, offering circular benefits for both energy and agricultural sectors.

Digital innovations are beginning to shape the next frontier in effluent management. The integration of Internet of Things (IoT), Artificial Intelligence (AI), and remote sensing technologies holds significant promise for real-time monitoring, predictive maintenance, and system optimization. These tools enable adaptive control, reduce operational costs, and support compliance with environmental regulations, making future effluent management systems not only smarter and more efficient but also more resilient to dynamic environmental conditions.

Emerging innovations in biomass valorization reveal a broader scope for agro-industrial waste beyond conventional effluent treatment. Techniques such as subcritical water extraction and thermochemical conversion have enabled the transformation of agricultural residues into high-value products, including animal feed (Huzir et al., 2024), soil amendment (Asmadi et al., 2023), biodegradable packaging (Palanisamy et al., 2024), biosorbents (Salsabila et al., 2024), and nanomaterials for pollutant degradation (Narayana et al., 2025). Additionally, subcritical and hydrothermal treatments facilitate the recovery of bioactive compounds such as antioxidants, polyphenols, and

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