

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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Abu Zahrim Yaser
Universiti Malaysia Sabah

Contributors

Rosnah Abdullah

Faculty of Science
Universiti Brunei Darussalam
Gadong, Brunei Darussalam

Abd Halim Md Ali

Department of Chemical & Environmental Engineering
Malaysia–Japan International Institute of Technology
(MJIT)
Universiti Teknologi Malaysia
Kuala Lumpur, Malaysia
and
Malaysia Japan Advanced Research Centre
Malaysia–Japan International Institute of Technology
(MJIT)
Universiti Teknologi Malaysia
Johor, Malaysia

Azlan Nur Rasyid Amin

Malaysia Japan Advanced Research Centre
Malaysia–Japan International Institute of Technology
(MJIT)
Universiti Teknologi Malaysia
Johor, Malaysia

Mohamed Afizal Mohamed Amin

Department of Chemical Engineering and Energy
Sustainability
Faculty of Engineering
Universiti Malaysia Sarawak
Sarawak, Malaysia

Maya Asyikin Mohamad Arif

Faculty of Resource Science and Technology
Universiti Malaysia Sarawak
Sarawak, Malaysia

Mohd Aizudin Abd Aziz

Faculty of Chemical Engineering Technology
University Malaysia Pahang Al-Sultan Abdullah
Pahang, Malaysia

Muhammad Saifullah Abu Bakar

Faculty of Integrated Technologies
Universiti Brunei Darussalam
Gadong, Brunei Darussalam

Rizkiy Amaliyah Barakwan

Environmental Engineering Study Program
Department of Biology
Faculty of Science and Technology
Universitas Airlangga, Indonesia

Muhammad Roil Bilad

Faculty of Integrated Technologies
Universiti Brunei Darussalam
Gadong, Brunei Darussalam

Dayang Norafizan Awang Chee

Faculty of Resource Science and Technology
Universiti Malaysia Sarawak
Sarawak, Malaysia

Mohamad Darwish

Faculty of Civil Engineering
Universiti Teknologi Malaysia (UTM)
Johor, Malaysia

Haidy Henry Dusim

Universiti Teknologi MARA Cawangan Sabah
Kota Kinabalu, Malaysia

Faranak Faghiri

Department of Environmental Science
Faculty of Natural Resources
Tarbiat Modares University
Noor, Iran

Nur Amira Fatihah

Faculty of Chemical Engineering Technology
University Malaysia Pahang Al-Sultan Abdullah
Pahang, Malaysia

Nurina Fitriani

Study Program of Environmental Engineering
Department of Biology
Faculty of Science and Technology
Universitas Airlangga
Surabaya, Indonesia

Muhammad Auni Hairunnaja

Faculty of Chemical Engineering Technology
University Malaysia Pahang Al-Sultan Abdullah
Pahang, Malaysia

Zubaidah Aimi Abdul Hamid

Faculty of Bioengineering and Technology
Universiti Malaysia Kelantan
Kelantan, Malaysia

Zubair Hashmi

Faculty of Integrated Technologies
Universiti Brunei Darussalam
Gadong, Brunei Darussalam

Hizriana Nuril Fitri Herryady

Food Security Research Laboratory
Faculty of Food Science and Nutrition
Universiti Malaysia Sabah
Sabah, Malaysia

Nurhamieza Md Huzir

Malaysia Japan Advanced Research Centre
Malaysia-Japan International Institute of Technology
(MJIT)
Universiti Teknologi Malaysia
Johor, Malaysia

Khairuddin Md Isa

Faculty of Chemical Engineering Technology
Universiti Malaysia Perlis
Perlis, Malaysia

Nur Afiqah Kamaludin

Study Program of Environmental Engineering
Department of Biology
Faculty of Science and Technology
Universitas Airlangga
Surabaya, Indonesia

Mohd Azraai Kassim

Department of Water and Environmental Engineering
Faculty of Civil Engineering
Universiti Teknologi Malaysia
Johor Bahru, Malaysia

Fikri Akmal Khodzori

Borneo Marine Research Institute
Higher Institution Centers of Excellence
Universiti Malaysia Sabah
Sabah, Malaysia

Junidah Lamaming

Faculty of Resource Science and Technology
Universiti Malaysia Sarawak
Sarawak, Malaysia

Siti Norasyiqin Abdul Latif

Innovation Centre in Agritechnology for Advanced
Bioprocessing (ICA)
Universiti Teknologi Malaysia
Johor, Malaysia

Wai Loan Liew

Department of Chemical and Environmental Engineering
(ChEE)
Malaysia-Japan International Institute of Technology
(MJIT)
Universiti Teknologi Malaysia
Kuala Lumpur, Malaysia
and
Metabolic Engineering and Molecular Biology (MEMO-
Bio) iKohza
Malaysia-Japan International Institute of Technology
(MJIT)
Universiti Teknologi Malaysia
Kuala Lumpur, Malaysia
and
Water and Wastewater Treatment (WWT) Research Group
Faculty of Civil Engineering
Universiti Teknologi Malaysia
Johor Bahru, Malaysia

Soh Kheang Loh

Energy & Environment Unit
Engineering & Processing Research Division
Persiaran Institusi
Kajang, Malaysia

Zul Ilham Zulkiflee Lubes

Biomass Energy Laboratory
Institute of Biological Sciences
Faculty of Science
Universiti Malaya
Kuala Lumpur, Malaysia

Claudeareena Gardling Malien

Faculty of Resource Science and Technology
Universiti Malaysia Sarawak
Sarawak, Malaysia

Muthukumaaran Manickam

Biomass Energy Laboratory
Institute of Biological Sciences
Faculty of Science
Universiti Malaya
Kuala Lumpur, Malaysia
and
Functional Omics and Bioprocess Development
Laboratory
Institute of Biological Sciences
Faculty of Science
Universiti Malaya
Kuala Lumpur, Malaysia

Khalida Muda

Metabolic Engineering and Molecular Biology (MEMO-Bio) iKohza
 Malaysia-Japan International Institute of Technology (MJIT)
 Universiti Teknologi Malaysia
 Kuala Lumpur, Malaysia
 and
 Water and Wastewater Treatment (WWT) Research Group
 Faculty of Civil Engineering
 Universiti Teknologi Malaysia
 Johor Bahru, Malaysia

Muhammad Abdurrahman Munir

Faculty of Resource Science and Technology
 Universiti Malaysia Sarawak
 Sarawak, Malaysia

Shaymaa Mustafa

Department of Mathematical Sciences
 Faculty of Science
 Universiti Teknologi Malaysia (UTM)
 Johor, Malaysia

Rinaldy Jose Nathanael

Environmental Engineering Program
 Faculty of Science and Technology
 Airlangga University
 Surabaya, Indonesia

Debbra Toria Nipo

Faculty Business, Economics and Accountancy
 Universiti Malaysia Sabah Centre for Economic
 Development and Policy
 Universiti Malaysia Sabah, Sabah, Malaysia

Katharina Oginawati

Environmental Management and Technology Research
 Group
 Environmental Engineering Department
 Bandung Institute of Technology
 Bandung, Indonesia

Siti Nur Hazwani Oslan

Food Security Research Laboratory
 Faculty of Food Science and Nutrition
 Universiti Malaysia Sabah
 Sabah, Malaysia

Saizal Pinjaman

Faculty Business, Economics and Accountancy
 Universiti Malaysia Sabah Centre for Economic
 Development and Policy
 Universiti Malaysia Sabah
 Sabah, Malaysia

Cheong Jia Qi

Universiti Teknologi MARA Cawangan Perak
 Malaysia Centre for Economic Development and Policy
 Malaysian Inbound Tourism Association, Perak, Malaysia

Danar Arifka Rahman

Study Program of Environmental Engineering
 Department of Biology
 Faculty of Science and Technology
 Universitas Airlangga
 Surabaya Indonesia
 and
 Indonesia Sustainable Environmental Technology
 Research Group
 Universitas Airlangga
 Surabaya, Indonesia

Sitti Fatimah Mhd Ramle

Faculty of Bioengineering and Technology
 Universiti Malaysia Kelantan
 Kelantan, Malaysia

Ahmad Faizal Abdull Razis

Natural Medicines and Products Research Laboratory
 Institute of Bioscience
 Universiti Putra Malaysia
 Selangor, Malaysia

Ain Nadirah Romainor

Faculty of Resource Science and Technology
 Universiti Malaysia Sarawak
 Sarawak, Malaysia

Muhammad Bukhari Rosly

Malaysia Japan Advanced Research Centre
 Malaysia-Japan International Institute of Technology
 (MJIT)
 Universiti Teknologi Malaysia
 Johor, Malaysia

Ruggero Rossi

Department of Environmental Health and Engineering
 Johns Hopkins University
 Baltimore, MD

Mehri Shabani

Department of Chemistry
 Group Analysis and Processes (GA&P)
 University of Angers
 Angers, France
 and
 ESAIP La Salle
 CERADE
 Saint-Barthélemy d'Anjou, France

Noor Fazliani Shoparwe

Faculty of Bioengineering and Technology
 Universiti Malaysia Kelantan
 Kelantan, Malaysia

Saima Sohni

Institute of Chemical Sciences
 University of Peshawar
 Peshawar, Pakistan

Pramila Tamunaidu

Department of Chemical & Environmental Engineering
Malaysia-Japan International Institute of Technology
(MJIT)

Universiti Teknologi Malaysia

Kuala Lumpur, Malaysia

and

Malaysia Japan Advanced Research Centre

Malaysia-Japan International Institute of Technology
(MJIT)

Universiti Teknologi Malaysia

Johor, Malaysia

Wan Abd Al Qadr Imad Wan-Mohta

Functional Omics and Bioprocess Development
Laboratory

Institute of Biological Sciences

Faculty of Science

Universiti Malaya

Kuala Lumpur, Malaysia

Abu Zahrim Yaser

Chemical Engineering Programme

Faculty of Engineering

Universiti Malaysia Sabah

Sabah, Malaysia

Jain Yassin

Universiti Teknologi MARA Cawangan Sabah
Kota Kinabalu, Malaysia

Habibollah Younesi

Department of Environmental Science

Faculty of Natural Resources

Tarbiat Modares University

Noor, Iran

Wong Sing Yun

Faculty Business

Economics and Accountancy

Universiti Malaysia Sabah Centre for Economic

Development and Policy

Universiti Malaysia Sabah

Sabah, Malaysia

Nik Nurul Anis Nik Yusoff

Faculty of Bioengineering and Technology

Universiti Malaysia Kelantan

Kelantan, Malaysia

Juliana Zaini

Faculty of Integrated Technologies

Universiti Brunei Darussalam

Jalan Tungku Link

Gadong, Brunei Darussalam

Editors

Abu Zahrim Yaser is an Associate Professor and Dean at Universiti Malaysia Sabah, holding a PhD from Swansea University, UK. He is the founder of the Kundasang Compost Living Lab and has published 18 books. He also served as a visiting scientist at the University of Hull, UK, and received the 2023 National Book Award.

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.

Junidah Lamaming is a Senior Lecturer at Universiti Malaysia Sarawak, Malaysia, specializing in nanocellulose, polymer composites, and sustainable biomaterials. An award-winning researcher and prolific author, she has published extensively and serves as a reviewer for numerous international journals.

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

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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