

Biomaterials, Bioengineering and Sustainability 4

Md. Faiyazuddin
Meghraj Suryawanshi *Editors*

Design and Processing of Green Materials


Exploring Sustainable Applications in
Medical and Pharmaceuticals Sciences


 Springer

Biomaterials, Bioengineering and Sustainability

Volume 4

Series Editors

Joaquim Miguel Oliveira , 3Bs Research Group
University of Minho
Barco, Portugal

Rui Luís Reis , AvePark - Parque de Ciência e Tecnologia
3B's Research Group
Barco, Portugal


Editorial Board

Antonella Motta , University of Trento
TRENTO, Italy


Biman Behari Mandal, Indian Institute of Technology Guwahati
Guwahati, India

Changyou Gao, Engineering, Rm 317 Polymer Bldg
Zhejiang University
Hangzhou, China

Khang Gilson, Dept of Polymer-Nano Science & Tech
Jeonbuk National University
Deokjin, Jeonju, Korea (Republic of)


Jeremy Teo , New York University Abu Dhabi
Abu Dhabi, United Arab Emirates

Ketul C. Popat, Scl.of Biomedical Engg. Dept. Mech.Engg
Colorado State University
Fort Collins, USA

Mario Monzon , University of Las Palmas de Gran Canaria
Las Palmas de Gran Canaria, Spain

Maurice Collins, School of Engineering
University of Limerick
Limerick, Ireland

Miguel Alaminos, Departamento de Histología
University of Granada
GRANADA, Spain

Kee Woei Ng , Nanyang Technological University
Singapore, Singapore

There is an urgent need to address the current paradigm shifts in bioengineering for Human Health aiming the creation of breakthrough tissue engineered products, manufacturing technologies and effective regenerative treatments for tackling different diseases/disorders in a personalized manner. Yet, the excessive costs and wastes related to the development and production of biomaterials and advanced therapy medicinal products, and the increasing use of plastics in cell culture methods and animal derived reagents has recognized the importance of decreasing the direct carbon footprint and thus, implement sustainable principles and solutions in the innovation ecosystem. The main goal of the volumes in Biomaterials, Bioengineering and Sustainability series is to catapult and consolidate new concepts and solutions towards the development of the next-generation of sustainable and eco-friendly biomaterials and tissue engineering and regenerative medicine approaches. Each volume will focus on the latest developments dealing with the identification of new sources of sustainable or recycled biomaterials, providing ideas for green technologies and methods that can be applied for biomaterials advanced processing and scaffolding strategies, and applications in biofabrication, tissue engineering, regenerative medicine, and drug delivery systems. It also aims to include the exploitation of renewable and sustainable source of human cells applied for cell therapies or in combination with sustainable biomaterials. The develop complex in vitro 3D/4D models and dynamic cell culture systems will be other subjects to be further explored from a sustainable perspective. This series aims to attract the contributions of leading experts in bioengineering, cell biology, materials engineering, and environmental sciences.


Md. Faiyazuddin • Meghraj Suryawanshi
Editors

Design and Processing of Green Materials

Exploring Sustainable Applications
in Medical and Pharmaceuticals
Sciences

 Springer

Editors

Md. Faiyazuddin 
Department of Pharmaceutics,
School of Pharmacy
Al-Karim University
Katihar, Bihar, India

Meghraj Suryawanshi
Department of Pharmaceutics
Sandip Institute of Pharmaceutical
Sciences (SIPS)
Affiliated To Savitribai Phule Pune
University (SPPU, Pune)
Nashik, Maharashtra, India

ISSN 2731-751X

ISSN 2731-7528 (electronic)

Biomaterials, Bioengineering and Sustainability

ISBN 978-3-031-91789-9

ISBN 978-3-031-91790-5 (eBook)

<https://doi.org/10.1007/978-3-031-91790-5>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2025

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

This book is lovingly dedicated to my beloved mother, **Sabiha Khatoon**, who has been the guiding light of my life—my source of strength, compassion, and unwavering support. Her prayers have been my protection, her wisdom my direction, and her love my foundation. She is the heart of our family and the soul of our home. Every accomplishment I achieve is built upon her sacrifices and unconditional love.

“And We have enjoined upon man [care] for his parents. His mother carried him, [increasing her] in weakness upon weakness, and his weaning is in two years. Be grateful to Me and to your parents; to Me is the [final] destination.”

—Surah Luqman (31:14)

“And lower to them the wing of humility out of mercy and say, ‘My Lord, have mercy upon them as they brought me up [when I was] small.’”

—Surah Al-Isra (17:24)

May Allah grant her a long life filled with health, happiness, and continued blessings. Ameen.

—Professor (Dr.) Md. Faiyazuddin

Preface

The escalating environmental challenges and the growing global demand for sustainable development have urged researchers, scientists, and industries to adopt eco-conscious approaches across various disciplines. In the biomedical and pharmaceutical sciences, this shift is both a necessity and a responsibility—one that prioritizes reducing ecological footprints while enhancing human health outcomes. It is in this spirit that the present volume, *Design and Processing of Green Materials: Exploring Sustainable Applications in Medical and Pharmaceuticals Sciences*, has been developed.

This edited book presents a comprehensive collection of recent advancements, research insights, and innovative applications in the realm of green biomaterials. Authored by leading experts and emerging scholars, the chapters address key issues related to sustainability in material design, synthesis, processing, and biomedical application. The book is structured to provide a holistic perspective, beginning with fundamental concepts and progressing through applied technologies and regulatory considerations.

Topics covered include biodegradable polymers, green chemistry methods for biomaterials synthesis, eco-friendly fabrication techniques, biomimetic strategies, and novel approaches in tissue engineering, regenerative medicine, and drug delivery. Additionally, the volume explores life cycle assessments, intellectual property landscapes, and regulatory frameworks that shape the future of sustainable biomedical practices.

The book opens with Chap. 1, which introduces the concept of green biomaterials, offering a foundational understanding of their significance, development challenges, and potential applications in health and sustainability. This sets the stage for Chap. 2, where the focus shifts to polymeric materials, discussing their synthesis, biodegradation, and growing role in drug delivery and tissue engineering. In Chap. 3, the authors explore environmentally benign chemical methods for material synthesis, promoting the use of renewable resources, solvent-free reactions, and energy-efficient processing techniques. Chapter 4 presents innovative approaches that integrate ecological responsibility into tissue engineering, from sustainable scaffold production to low-energy bioprocessing systems. Chapter 5 delves into the fabrication of medical devices using green techniques such as 3D bioprinting and electrospinning, emphasizing the use of biodegradable inputs. Complementing this, Chap. 6 illustrates how regenerative medicine offers sustainable, long-term therapeutic

solutions that reduce dependency on synthetic implants and prolonged pharmacological treatments. Nature-inspired design takes center stage in Chap. 7, where the authors discuss the design and functionality of biomaterials modeled after natural structures. Chapter 8 builds upon this by examining how these materials interact with biological systems, influencing cell behavior and contributing to functional tissue regeneration. In Chap. 9, the spotlight is on eco-designed scaffolds that not only support tissue regrowth but also minimize environmental burden through sustainable sourcing and degradation. This theme continues in Chap. 10, which surveys cutting-edge bioprinting strategies that allow precise control over architecture and composition, using biocompatible and biodegradable materials. Chapter 11 discusses green innovations in drug delivery, particularly biodegradable and stimuli-responsive systems that reduce systemic toxicity and environmental impact. Natural polymers take precedence in Chap. 12, where plant-derived materials are explored for their roles in wound healing, drug encapsulation, and tissue scaffolds. Chapter 13 presents clinical applications of bioactive natural materials in the treatment of chronic wounds, emphasizing the dual benefits of efficacy and biodegradability. Shifting focus to environmental and production considerations, Chap. 14 provides tools and methodologies for evaluating the environmental impact of biomaterials across their entire lifecycle. In Chap. 15, readers are introduced to the regulatory and innovation landscape, showcasing how green biomaterials are advancing through patent filings, clinical validation, and formulation development. Finally, Chap. 16 addresses the safety, standardization, and regulatory frameworks necessary to ensure the responsible adoption of biomaterials in healthcare.

Together, these chapters provide a comprehensive overview of sustainable biomaterials, addressing both advances and challenges in their development, processing, application, and regulation. The book bridges fundamental research with translational potential, offering insights that are critical for researchers, clinicians, policymakers, and industry professionals seeking to build a greener and more sustainable future in medicine and pharmaceuticals.

We extend our sincere thanks to all the contributors for their dedicated efforts, and to Springer Nature for supporting this initiative. We hope this volume serves as both a resource and an inspiration for future innovations in green material science.

Katihar, Bihar, India
Nashik, Maharashtra, India

Md. Faiyazuddin
Meghraj Suryawanshi

Acknowledgments

We thank Almighty, the All-Merciful, the All-Compassionate, for His countless blessings and guidance throughout this endeavor. We sincerely thank each and every contributor for participating in this beneficial work.

First and foremost, we extend our sincere thanks to all the contributing authors for their valuable research contributions and dedication to advancing sustainable biomaterials. We are also deeply grateful to the reviewers and subject experts who provided insightful feedback to enhance the quality of each chapter.

We would like to acknowledge **Jamia Hammad**, **Sandip University**, and **Saveetha University**—our esteemed institutions—for providing strong foundations for our academic and research pursuits.

Our sincere appreciation goes to the editorial and production team at **Springer Nature**, especially **Ramya Ravichandran**, Senior Editor; **Eva Loerinczi**, Senior Production Editor; **Peggy Papandreou**, Publishing Manager; **Immaculate Jayanthi**, Assistant Editor; and **Gonzalo Cordova**, Senior Editorial Assistant. Their professionalism, patience, and support were invaluable throughout the publication process.

We also extend our thanks to **Dr. Miguel Oliveira** (i3Bs, University of Minho) for his invaluable guidance and support.

The volume editors would also like to express their gratitude to **Springer Nature** and all its employees for offering a professional environment that fosters effective collaboration with subject matter experts.

We are thankful to our colleagues, students, and collaborators for their encouragement and intellectual engagement during the development of this volume.

Lastly, we extend our deepest gratitude to our families for their unwavering love, prayers, and support, which have been our constant source of strength.

To all who contributed directly or indirectly, we offer our sincere thanks.

Contents

1	Green Biomaterials: Challenges and Opportunities	1
	Bindiya Chauhan, Bhuvnesh Kumar Singh, Anil Kumar, Neelanchal Trivedi, Md. Faiyazuddin, and Thomas J. Webster	
2	Biodegradable Polymers: Advances in Sustainable Biomaterials	29
	Satish Mandlik, Deepa Mandlik, and Amarjitsing Rajput	
3	Green Chemistry Approaches in Biomaterials Synthesis	67
	Priya Jain, Juhi Bhadoriya, Sheetal Mane, Kuldeep Vinchurkar, and Meghraj Vivekanand Suryawanshi	
4	Tissue Engineering Strategies for Environmental Sustainability	99
	Hasan Ali, Md. Faiyazuddin, Md. Akbar, and Nodirali Normakhamatov	
5	Bio-Fabrication Techniques for Eco-Friendly Biomedical Devices	123
	Moumita Das Kirtania, Radheshyam Pal, Sumel Ashique, Ankit Kumar, and Sanjay Dey	
6	Regenerative Medicine-A Promising Approach to Address the Global Healthcare Challenges and Promoting Sustainability	157
	Shahid Nazir Wani, Ishrat Zahoor, Junaid Tantray, Goli Venkateshwarlu, Pradyumn Tiwari, Shahbaz Eqbal, Md. Faiyazuddin, and Amer Ahmed Syed	
7	Biomimetic Materials: Nature-Inspired Solutions for Sustainability	181
	Mohammad Intakhab Alam, Md Sajid Ali, Nawazish Alam, Md. Faiyazuddin, and Sarfaraz Ahmad	
8	Cell-Material Interaction in Sustainable Biomedical Engineering . . .	205
	Sourav Ghosh, Amartya Sen, Abhishek Digar, Biswajit Basu, Swarnali Dutta, Swarupananda Mukherjee, and Sudarshan Singh	

9	Bioinspired Scaffolds for Tissue Regeneration and Environmental Impact	225
	Anas Islam, Ambareen Fatima Ahmed, Widhiliika Singh, Md. Faiyazuddin, Usama Ahmad, and Faiyaz Shakeel	
10	Bioprinting Technologies for Sustainable Tissue Engineering	277
	Parth Surati, Priyanka Pawale, and Meghraj Suryawanshi	
11	Recent Advancement in Biomaterial-Based Drug Delivery System . . .	293
	Manjusha Bhange, Kuldeep Vinchurkar, Ankita Bhadoriya, Sheetal Mane, and Meghraj Vivekanand Suryawanshi	
12	Polysaccharides Based Gums and Mucilage: As Potential Biomaterial.	315
	Hitendra S. Mahajan, Ujwaldip Vijay Deore, Meghraj Suryawanshi, and Rahul Sarode	
13	Natural Biomaterials Used in Wound Healing and Diabetic Foot	329
	Md Jasim Uddin, Amol D. Gholap, Iqra Zulfiqar, Samiha Binte Sadiq, Sharmin Lucky, and Khadiza Akter Lubna	
14	Life Cycle Assessment of Biomaterials: Towards Sustainable Production and Consumption	369
	Sonia Gupta, Dinesh Kumar, Monika Sharma, and Rajni Tanwar	
15	Patents, Clinical Trials and Dosage Form Based on Biomaterials	391
	Mohd Sayeed Shaikh, Rupesh R. Kurhade, Shaikh Shahbaz A. Majeed, Mujtaba Md Shaikh, Paresh R. Mahaparale, Mayura A. Kale, Mohd Usman Mohd Siddique, Md. Faiyazuddin, and Yahya E. Choonara	
16	Regulatory Concern for Biomaterial and Its Toxicity	433
	Shachi Patel, Swati Sharma, Jalpa Suthar, and Meghraj Suryawanshi	



Bioinspired Scaffolds for Tissue Regeneration and Environmental Impact

9

Anas Islam, Ambareen Fatima Ahmed, Widhilika Singh,
Md. Faiyazuddin, Usama Ahmad, and Faiyaz Shakeel

Abstract

Bioinspired scaffolds are revolutionizing the field of tissue regeneration by mimicking the complex structures and functionalities of natural tissues. The concepts of bioinspiration are examined in this chapter, along with how natural patterns might be adapted into artificial scaffolds to improve tissue regeneration and repair. Along with cutting-edge manufacturing techniques including electrospinning, 3D printing, and self-assembly approaches, it covers a variety of bioinspired scaffold types, such as polymer-based, ceramic-based, composite, and nanostructured scaffolds. Additionally, the chapter emphasizes how crucial scaffold functionalization is for enhancing bioactivity, cell adhesion, and proliferation. It also discusses how the manufacture of scaffolds affects the environment, highlighting the need of sustainable processes and eco-friendly materials. Examples from the fields of bone, cartilage, skin, and brain tissue engineering show how bioinspired scaffolds may be used practically and effectively. The difficulties, prospects, and possibilities of bioinspired scaffolds in promoting tissue

A. Islam

Faculty of Pharmacy, Integral University, Lucknow, India

School of Pharmaceutical Sciences, Integral University, Lucknow, India

A. F. Ahmed · W. Singh

School of Pharmaceutical Sciences, Integral University, Lucknow, India

Md. Faiyazuddin

School of Pharmacy, Al – Karim University, Katihar, Bihar, India

U. Ahmad (✉)

Faculty of Pharmacy, Integral University, Lucknow, India

F. Shakeel (✉)

Department of Pharmaceutics, College of Pharmacy, King Saud University,
Riyadh, Saudi Arabia

engineering while reducing environmental effect are covered in the chapter's conclusion.

Keywords

Bioinspired scaffolds · Tissue regeneration · Biomaterials · Environmental impact · Fabrication techniques

9.1 Introduction

Tissue regeneration represents a pivotal aspect of regenerative medicine, focusing on the restoration of damaged or diseased tissues to their original state of function (Salgado et al. 2013). Unlike conventional treatments that may rely on prosthetics or donor tissues, tissue regeneration leverages the body's inherent ability to heal, aiming to stimulate and guide this natural process (Colazo et al. 2019). Significant advancements in the principles of tissue regeneration have been achieved through the fields of stem cell biology, molecular biology, and biomaterials science. Together, these domains have made it feasible to develop complex techniques that mimic the mechanical and biological features of natural tissues, providing effective substitutes for conventional treatment strategies (Xia et al. 2018). Because chronic illnesses, traumas, and aging-related tissue deterioration are becoming more common, there is a greater need than ever for efficient tissue regeneration treatments. Irreversible tissue damage is often caused by conditions including osteoarthritis, cardiovascular disorders, and nerve injuries, which are difficult for traditional medical therapies to effectively cure (Vahidi et al. 2024; Banerjee et al. 2021). Within this particular framework, tissue regeneration serves as more than just a treatment choice, but rather a crucial need that has the capacity to reinstate functionality and enhance the overall well-being of countless individuals over the globe. Scaffolds are vital for successful tissue regeneration due to their temporary nature, which facilitates cell adhesion, proliferation, and differentiation. By providing the necessary foundation, scaffolds aid in the creation of new tissue and gradually disintegrate to make room for the regenerated structure. Scaffold design and manufacturing have advanced by using bioinspired techniques that mimic natural tissues, hence improving tissue regeneration (Yari et al. 2022; Hussain et al. 2023).

9.1.1 Importance of Bioinspired Scaffolds

Bioinspired scaffolds mark a significant progress in tissue engineering as they offer designs that closely resemble the complex architecture and functional characteristics of real tissues. These scaffolds are designed to mimic the tissues they are meant to substitute regarding their microstructure, mechanical properties, and metabolic condition. In doing so, they establish an environment that better supports cell growth and tissue development, greatly enhancing the effectiveness of regenerative