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

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.

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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

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

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.

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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 Hamdard**, **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

Bioinspired Scaffolds for Tissue Regeneration and Environmental Impact

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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

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Md. Faiyazuddin, M. Suryawanshi (eds.), *Design and Processing of Green Materials*, Biomaterials, Bioengineering and Sustainability 4,
https://doi.org/10.1007/978-3-031-91790-5_9

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