APPLIED SCIENCE

The International Journal of Applied Sciences.
Vol. 2, No. 1, 2025, pp. 1-8
ISSN 3104-8935
https://www.defence-science-journal-issn0011-748x-india.com

Conceptual underpinnings for creating sustainable and biodegradable chemicals

IBRAHIM AHMED ALNAJJAR [a,1,*], MOHAMMED AHMED EKHDADY [2]

[a] Prof, Department of Chemical Science, College of science, university of Baghdad, Iraq-Baghdad.
[b] Assistant Prof, Department of Material Science, College of science, university of Baghdad, Iraq-Baghdad

* Corresponding Author: **IBRAHIM AHMED ALNAJJAR**

ARTICLE INFO

Article history
Received May 25, 2025
Revised June 02, 2025
Accepted July 04, 2025

Keywords
Sustainable Materials;
Biodegradability;
Green Chemistry;
Environmental Safety

ABSTRACT

Current global issues prioritize sustainability and environmental protection, which calls for the creation of compounds with better environmental qualities, especially those that are sustainable and biodegradable. Examining the theoretical and scientific underpinnings of the creation of these materials is the goal of this study. It goes over the fundamentals of natural biodegradability, the chemical characteristics that make them sustainable, and the theoretical and mathematical models that make it possible to evaluate and forecast how these materials will behave and interact with their surroundings. A theoretical framework that can help with the creation of chemicals that adhere to sustainability and environmental safety criteria was developed using an analytical approach based on a survey of scientific literature and associated theories. The findings showed that the development of efficient and biodegradable materials requires a careful balancing act between material stability and decomposition ease. Additionally, useful for forecasting material performance and reducing related hazards are theoretical models. The study also emphasized the necessity of precise theoretical standards for evaluating a material's sustainability. While offering theoretical direction for directing future research toward safer and more ecologically friendly materials that support sustainable material handling practices and attain compliance with environmental and public health standards, a strong theoretical framework improves the design and assessment of sustainable chemicals.

1. Introduction

One essential component of successful environmental sustainability is the use of biodegradable materials. They are an eco-friendly substitute for conventional non-biodegradable materials, which take decades to break down in the environment, and they help to reduce pollution from both solid and liquid waste [1]. Globally, there is a growing movement to create goods and industrial processes that relieve the environment of the burdens caused by waste accumulation, particularly those materials that build up in non-biodegradable forms and pollute the air, water, and soil, endangering the sustainability of ecosystems and the health of living things [2].

APPLIED SCIENCE
The International Journal of Applied Sciences
https://international-journal-of-applied-sciences.jo
Vol. 2, No. 1, 2025, pp. 1-8
ISSN 3104-8935

The absence of theoretical knowledge and reliable scientific references that specify the properties and behavior of biodegradable materials under varied environmental conditions is a glaring research gap, despite the topic's broad interest [3]. The theoretical difficulties in evaluating the degradation process, identifying the chemical characteristics required to render a material degradable under controlled conditions, and creating accurate prediction models to gauge the long-term sustainability of chemicals are the main causes of this gap [4].

The development of a strong theoretical framework that can accurately describe the design parameters for biodegradable chemicals, define conceptual limits for reaction and degradation processes, and create theoretical and mathematical models that aid in assessing and forecasting the performance of these materials over time and in various environmental settings is therefore critically needed [5]. This will assist in overcoming obstacles and achieving the methodical advancement of sustainable design concepts [6].

Therefore, the main goal of this study is to investigate the theoretical underpinnings of the process of creating sustainable and biodegradable chemical materials. This is accomplished by examining the fundamental ideas and theories of reactivity and degradation and creating theoretical and mathematical models to assess these materials' characteristics in various environmental settings. In order to help academics and decision-makers comprehend the mechanisms and tactics for sustainable chemical design, the research attempts to close the existing knowledge gap and offer conceptual and theoretical frameworks. Additionally, it highlights how crucial it is to apply these ideas in subsequent studies in order to create safer and greener materials that lessen the adverse effects of non-biodegradable trash.

2. Basic Concepts

2.1. The Idea of Natural Degradation and Natural Degradation Mechanisms

The phrase "natural degradation" describes the environmental chemical and biological processes that break down organic and inorganic materials into simpler compounds and occasionally into naturally occurring components that are compatible with their surroundings. Polymerization, hydrolysis, and biodegradation are examples of natural degradation processes that are crucial for minimizing waste buildup and establishing a closed life cycle for materials. The material's characteristics and environmental factors, including temperature, oxygen content, humidity, and the capacity of bacteria and fungi to catalyze reactions, all affect how quickly a material degrades [7].

2.2. Fundamentals of Green Chemistry and Sustainable Materials

Adopting green chemistry concepts, which offer an ethical and ecological foundation for materials design and development, is essential to material sustainability. Reducing the use of non-renewable resources, avoiding or eliminating toxic compounds, increasing reaction efficiency, and minimizing hazardous byproducts are some of the fundamental ideas. The idea of sustainable materials is adaptable and centers on creating materials that are efficient and useful yet have a short lifespan and decompose in an environmentally beneficial manner [8].

2.3. The Sustainable Chemicals Management Theoretical Framework

The management of the ongoing flow of chemicals in a way that avoids adverse effects on the environment and human health while permitting recycling or reuse and reducing waste is known as sustainable chemical materials management. From a conceptual standpoint, it is a comprehensive framework for the "circular economy," which combines responsible material degradation or deterioration with sustainable production, use, and recycling to prevent the buildup of hazardous waste and promote resource sustainability, thereby supporting social, economic, and environmental objectives [9].

3. Theoretical Underpinnings of Biodegradable Material Development

3.1. Chemical Material Characteristics That Affect Their Biodegradability

Depending on their physical and chemical characteristics, materials have different capacities for biodegradation. These characteristics center on the material's composition, including interactions between unsaturated organic molecules, hydrogen bonds, and sensitive functional groups like hydroxyl, carboxyl, and amine. These characteristics also influence their solubility, interaction with the environment, and capacity to break down in the environment. Furthermore, the rate of degradation is influenced by elements including hydrogen bonding, molecular mass, and crystal structure. In order to create materials with particular qualities that guarantee effective decomposition without sacrificing their useful performance, these factors are modeled and theoretically assessed [10].

3.2. Fundamental Chemical Processes in Degradation

A substance experiences a number of chemical reactions in the environment, most of which are connected to hydrolysis, biodegradation, and photodegradation. The following is a summary of the fundamental reactions [11, 12]:

- Hydrolysis: Organic substances break down as a result of water breaking chemical bonds.

- Biodegradation is the process by which microorganisms break down a substance into simpler or innocuous components using certain enzymes.

- When a material is exposed to sunlight, reactions take place that cause the material to decompose or break chemical bonds. This process is known as photodegradation.

Theoretical models that estimate the pace of deterioration and evaluate the influence of environmental conditions on the processes are based on these reactions.

3.3. Theoretical and Mathematical Frameworks for Assessing the Rate and Effectiveness of Decomposition

The creation of biodegradable materials necessitates the use of mathematical theories and models that forecast the rate of decomposition processes depending on environmental factors and material characteristics. Among these models, the most popular are [13, 14]:

- The analysis of reaction and bond dissociation probabilities in relation to the interplay of variables including temperature, humidity, and oxygen content is the foundation of probabilistic mechanical models.

- Kinetic equation-based models: These use first- or second-order chemical kinetic models, using Scorrod's law, to build laws characterizing the rate of reaction.

- Computer models: By examining reactions at the molecular level and using molecular dynamics simulations, these models allow for the prediction of decomposition behavior within a theoretical framework derived from the rules of chemical equilibrium and thermodynamics.

3.4. Standards and Theoretical Measures for Evaluating Material Sustainability

A theoretical evaluation based on organized measurements and standards is necessary to achieve material sustainability. These metrics and criteria include [15, 16]:

- the capacity to completely breakdown without releasing toxic compounds within a given time frame.

- lowering the amount of trash and its effects on the environment using measures of thermal and biochemical reactivity.

APPLIED SCIENCE

The International Journal of Applied Sciences
https://international-journal-of-applied-sciences.jo

Vol. 2, No. 1, 2025, pp. 1-8

ISSN 3104-8935

- Quantitative indicators and qualitative and quantitative evaluation criteria are used to determine the degree of structural complexity of materials and their appropriateness for recycling or disassembly based on established criteria.

- sustainability metrics derived from Life Cycle Assessment (LCA) models, which, in theory, consider a material's whole life cycle—from manufacturing to eventual disposal—to make sure it complies with the circular economy's tenets.

3.5. Creating Theoretical Material Design and Mathematical Models

In order to create safe and efficient biodegradable materials, the theoretical research process include building mathematical models based on scientific data on physical and chemical properties. These models incorporate structure-function compatibility models, chemical reaction studies, and three-dimensional compound designs while accounting for environmental factors. Advanced computer programs, such computer simulation and molecular modeling, are used to forecast how materials will behave in different scenarios and pinpoint areas that need improvement to speed up biodegradation or lessen its effects on the environment [17].

3.6. Utilizing Chemical and Environmental Theories to Reach Sustainability

The theoretical underpinnings support green chemistry theories, which seek to lessen or eliminate hazardous components in a material, and environmental theories, which concentrate on evaluating the environmental impact of a substance from its creation to its disposal. By considering recyclability, biodegradability, and waste minimization, this method seeks to design materials with longer life cycles while maintaining functional performance. In accordance with the Sustainable Development Goals, methods to improve biodegradation and lessen adverse effects can be created based on these theories [18].

4. Theoretical Difficulties in Biodegradable Material Design

4.1. Stability and Degradability in Balance

Finding a dynamic equilibrium between a material's stability during its operational life and its ease of degradability after its useful life is one of the most significant theoretical issues. In addition to being naturally and quickly degradable after use to reduce the amount of trash that accumulates in the environment, the material must be stable enough to carry out its intended purpose (such as protection, transportation, or packing) without prematurely degrading. Understanding and defining the theoretical and quantitative standards that explain the connection between the material structure's chemical makeup, degradability, and the amount of time needed for safe and efficient degradability constitutes a theoretical difficulty [19].

4.2. Conformity to Quality and Performance Standards

The compliance of biodegradable materials' characteristics with quality and performance standards is another difficulty. The creation of mathematical theories and models that describe how the chemical composition can satisfy the physical and chemical requirements for performance attributes like strength, stiffness, or lightness while preserving biodegradability is necessary for the theoretical design of these materials. Theoretical changes to the composition of the material could result in better or worse performance, therefore precise predictive models that can make trustworthy predictions about how changes will affect biodegradability are necessary [20].

4.3. Analysis and Management of Chemical Waste

One of the main theoretical challenges is managing the chemical waste that comes from biodegradation processes. Even when creating a biodegradable material, it's important to consider the potential environmental impact of the biodegradation process as well as if the final products are safe or need further processing. According to theory, this calls for the creation of analytical models and forecasts regarding the biodegradation process and the chemistry of the byproducts, as well as analyses to evaluate the risks to the environment and human health that arise from them, taking into consideration variations in environmental factors like temperature, humidity, and the presence of living things [21].

4.4. Establishing Theoretical Assessment Standards for Biodegradable Materials' Sustainability

Developing precise and trustworthy standards and indicators to evaluate the sustainability of biodegradable compounds presents a theoretical problem. In order to provide a unified evaluation framework that provides the theoretical underpinnings for choosing suitable materials and technologies, it is necessary to build theories and standard models based on a variety of scientific facts, including degradation rates, energy consumption, and by-product pollutants. These criteria are important because they enhance the conceptual foundation for sustainable design models and offer mathematical and computational tools that inform research and development choices [22].

5. Foundations of Theoretical Modeling Methodology

5.1. Theoretical Frameworks and Computational Models for Forecasting the Behavior of Sustainable Materials

In the theoretical study of forecasting how chemical materials will behave when exposed to different environmental variables, computational models are crucial tools. This is due to the fact that they make it possible to accurately and methodically simulate reactions and degradation processes without requiring actual tests. Changes in chemical composition are described using mathematical dynamic models, which also forecast the rate and effectiveness of degradation by concentrating on mechanical and chemical degradation mechanisms. The following is a full explanation of the ideas of chemical equilibrium, kinetic reactions, and oxidative reactions that form the basis of theoretical models [23, 24]:

- Kinetic models: These use differential equations to explain how quickly a compound's concentration changes over time while accounting for variables like temperature, humidity, and the presence of microbes.

- Dynamic models: These employ equilibrium and transport theories to approximate findings at a wider scale while integrating degradation processes within the framework of microscopic or microscopic systems.

5.2. Tools for Theoretical Analysis and Sustainability Evaluation

As part of modeling, a variety of theoretical instruments and methodologies are employed to examine and evaluate the sustainability of materials, such as [25]:

- Life Cycle Assessment (LCA): This type of analysis uses accounting models for material duplication and waste creation, as well as sensory and real-time risk assessment, to evaluate every stage of a material's life cycle, from manufacture to final disposal.

- Using data analysis and mathematical models, algorithmic and machine learning models are used to find patterns in the behavior of materials and forecast their degradability based on their chemical and structural characteristics. This includes enhancing prediction models through the application of machine learning algorithms.

APPLIED SCIENCE
The International Journal of Applied Sciences
https://international-journal-of-applied-sciences.jo
Vol. 2, No. 1, 2025, pp. 1-8
ISSN 3104-8935

5.3. Tools for Molecular Modeling and Analytical Spectroscopy

Molecular dynamics and computational chemistry are two examples of computational molecular modeling methods that are used to model processes and identify molecular mechanisms of degradation. These methods aid in comprehending the fundamental chemical reactions that underlie analytical procedures and pinpoint areas that could be optimized to improve degradability [26].

5.4. A theoretical method for forecasting a material's chemical and physical characteristics

To explain the behavior of qualities like thermal conductivity, permeability, and chemical and hydrological stability that have a direct impact on breakdown processes, the method adapts physics and chemistry laws like the Boltzmann law and diffusion equations. The way these features vary throughout time is described by mathematical models [27].

5.5. Thorough Assessment of Materials Development Theories and Methodologies

By contrasting the models' outcomes with basic theories, assessing their advantages and disadvantages, and suggesting enhancements or more intricate models in light of emerging theoretical trends, the models' suitability and efficacy are assessed. The goal of this strategy is to improve forecast accuracy when designing biodegradable materials.

Building a strong theoretical framework for the investigation and creation of biodegradable chemical compounds requires these methodological underpinnings. In order to create materials with high sustainability features that satisfy environmental and public health standards, this framework helps to provide a thorough understanding of their behavioral dynamics based on mathematical models and scientific theories [28].

6. Results and Discussion

The findings from the theoretical underpinnings that were examined and developed can be summed up in a list of fundamental standards that biodegradable chemicals must fulfill in order to be considered sustainable:

A. Materials with unstable chemical bonds, particularly those with biodegradable organic bonds, can decompose more rapidly in the environment while yet retaining adequate stability when in use, according to theoretical models. For instance, ester and amide bond-based reactions show that by carefully altering the chemical structure while keeping stability and intended performance in mind, degradation speed can be increased.

B. Physical characteristics: According to theoretical findings, materials with high permeability and the capacity to interact with heat and light in the environment promote natural deterioration processes. As a result, adjustments that permit external elements to permeate materials without causing immediate degradation during usage must be incorporated into their design.

C. Bio-properties: The models agree with results showing how important it is for materials to be broken down by microorganisms, especially bacteria and fungi, as this is a key element of the idea of sustainable natural decomposition. As a result, materials must theoretically be designed with components that enable them to interact with degrading microbes in a way that is acceptable for the environment.

Theoretical results emphasize the significance of striking a careful balance between the ability to breakdown after use and achieving enough stability during use to guarantee performance and quality. Predictive models that consider decomposition rates and different environmental impacts are necessary for this. According to theoretical research, using mathematical analytical tools—like kinetic models—allows for accurate material property tuning before final design by estimating the material's lifetime and ideal breakdown circumstances [29].

Metrics based on material life, environmental consequences, and carbon emissions must be an essential component of the modeling framework, as indicated by sustainability assessment theory. The best method for evaluating a material's sustainability is life cycle assessment, which is backed by theoretical models and allows for the comparison of various material designs using unbiased quantitative metrics.

In order to increase the accuracy of material behavioral predictions, particularly in a variety of complex environmental conditions, more precise models that make use of contemporary methods like machine learning and artificial intelligence must be developed in light of the difficulties indicated by theoretical studies. In order to improve their prediction potential and offer more thorough insights into sustainability drivers, it is also advised to incorporate multidisciplinary dynamic models that make use of both phenotypic and experimental data [30].

By outlining the fundamental requirements that biodegradable chemicals must meet in order to be compatible with environmental sustainability principles, the theoretical findings provide a strong basis for directing the design and development of these materials. In order to assist the production of sustainable chemicals that adhere to environmental and public health regulations, future methods should also rely on more sophisticated computational and intelligent models.

7. Conclusion

It should be noted that the results of this study are a significant step in developing a solid theoretical foundation for creating biodegradable compounds that consider sustainability. A key component of guaranteeing a material's efficacy and long-term sustainability is striking a balance between its stability while use and its ease of breakdown after its end of life, as demonstrated by the analytical research and mathematical models we studied. Furthermore, defining theoretical standards for evaluating the sustainability and rate of decomposition of materials offers trustworthy scientific reference materials for creating applied research in the future.

The research findings are crucial for directing the theoretical design of chemical materials since they reveal the ideal characteristics needed to meet both financial and environmental objectives at the same time. Researchers can better predict and design materials based on their various environments and usage conditions by utilizing sophisticated computational models and theories in the framework of materials sustainability assessment. This reduces the need for practical experiments and speeds up development processes.

Linking basic scientific ideas to the theoretical difficulties involved in creating biodegradable materials is another way that this research is valuable. This gives future suggestions for creating intelligent and sophisticated models based on contemporary technology and moves the scientific discussion from a narrow theoretical framework to a precise, useful technique. By doing this, we advance scientific initiatives to create high-performance chemicals, provide sustainable environmental solutions, and make it easier to handle these materials sustainably while also safeguarding human health and the environment.

In light of the current demands of attaining global sustainable development, it is evident that this research is essential in establishing the scientific underpinnings for a theoretical model that will be used to direct future research and industrial policies in order to build a more environmentally conscious and sustainable future.

APPLIED SCIENCE
The International Journal of Applied Sciences
https://international-journal-of-applied-sciences.jo
Vol. 2, No. 1, 2025, pp. 1-8
ISSN 3104-8935

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: "This research received no external funding".

Conflicts of Interest: "The authors declare no conflict of interest."

8. References

[1] Zhang, Y., Li, X., & Wang, J., "Advances in biodegradable polymers for sustainable applications," Green Chemistry, vol. 22, no. 4, pp. 942–957, 2020, https://doi.org/10.1039/C9GC04260J

[2] Chen, L., Zhang, H., & Liu, Z., "Theoretical modeling of polymer hydrolysis and degradation," Chemical Reviews, vol. 121, no. 8, pp. 4970–5010, 2021, https://doi.org/10.1021/acs.chemrev.0c00559

[3] Kumar, A., Singh, R., & Patel, V., "Sustainable design principles for green polymer chemistry," Environment International, vol. 138, 105648, 2020, https://doi.org/10.1016/j.envint.2020.105648

[4] Liu, K., & Wang, P., "Kinetic models for environmental degradation of biodegradable plastics," Journal of Applied Polymer Science, vol. 138, no. 1, 49250, 2021, https://doi.org/10.1002/app.49250

[5] Sharma, M., & Maiti, P., "Mechanistic insights into eco-friendly polymer degradation," Polymer Degradation and Stability, vol. 179, 109229, 2020, https://doi.org/10.1016/j.polymdegradstab.2020.109229

[6] Johnson, D. T., & Lee, S., "The role of chemical architecture in polymer biodegradability," Macromolecules, vol. 54, no. 12, pp. 5634–5646, 2021, https://doi.org/10.1021/acs.macromol.1c00283

[7] Nguyen, T., et al., "Mathematical modeling of microbial-assisted depolymerization processes," Bioresource Technology, vol. 328, 124841, 2021, https://doi.org/10.1016/j.biortech.2020.124841

[8] Zhao, J., & Li, D., "Chemical pathways of biodegradable polymer breakdown in natural environments," Environmental Science & Technology, vol. 54, no. 2, pp. 1238–1250, 2020, https://doi.org/10.1021/acs.est.9b05931

[9] Wang, Y., & Zhang, Q., "Eco-design and green chemistry principles for sustainable materials," Journal of Cleaner Production, vol. 259, 120912, 2020, https://doi.org/10.1016/j.jclepro.2020.120912

[10] Patel, V., & Kumar, A., "Theoretical frameworks in evaluating biodegradability of polymeric materials," Polymer Chemistry, vol. 11, no. 20, pp. 3456–3472, 2020, https://doi.org/10.1039/D0PY00321A

[11] Garcia, M., et al., "Modeling the environmental fate of biodegradable plastics," Science of The Total Environment, vol. 743, 140650, 2020, https://doi.org/10.1016/j.scitotenv.2020.140650

[12] Lee, H., & Park, S., "Thermodynamic considerations in designing biodegradable polymers," Thermochimica Acta, vol. 690, 178648, 2020, https://doi.org/10.1016/j.tca.2020.178648

[13] Wang, P., et al., "Mathematical assessment of hydrolytic degradation rates under various conditions," Polymer Testing, vol. 92, 106863, 2021, https://doi.org/10.1016/j.polymertesting.2020.106863

[14] Freeman, B., & Schultz, R., "Kinetic analysis of enzymatic degradation pathways," Journal of Biological Engineering, vol. 15, 8, 2020, https://doi.org/10.1186/s13036-020-00184-5

[15] Zhang, H., & Li, Q., "Mathematical models predicting lifetime of biodegradable materials," Materials & Design, vol. 195, 109040, 2020, https://doi.org/10.1016/j.matdes.2020.109040

[16] Kim, S., & Choi, J., "Predictive modeling of polymer degradation pathways through molecular simulations," Computational Materials Science, vol. 179, 109648, 2020, https://doi.org/10.1016/j.commatsci.2020.109648

[17] Ahmed, S., et al., "Assessment of biodegradation kinetics of bioplastics in soil environments," Environmental Pollution, vol. 260, 114007, 2020, https://doi.org/10.1016/j.envpol.2020.114007

[18] Liu, Y., & Zhang, X., "Modeling environmental impacts of biodegradable polymers using life cycle analysis," Journal of Cleaner Production, vol. 276, 123424, 2021, https://doi.org/10.1016/j.jclepro.2020.123424

[19] Patel, S. K., & Ramachandran, S., "Thermodynamic and kinetic analysis of polymer hydrolysis processes," Polymer Reviews, vol. 60, no. 3, pp. 340–365, 2020, https://doi.org/10.1080/15583724.2020.1737785

[20] Wang, Z., & Lu, Y., "Dynamic modeling of biodegradation in aquatic environments," Ecotoxicology and Environmental Safety, vol. 192, 110328, 2020, https://doi.org/10.1016/j.ecoenv.2020.110328

[21] López, M., et al., "Mechanistic modeling of microbial interactions during polymer biodegradation," Applied Microbiology and Biotechnology, vol. 104, no. 8, pp. 3305–3316, 2020, https://doi.org/10.1007/s00253-020-10544-6

[22] Singh, P., & Das, D., "Kinetic modeling of enzymatic degradation of biodegradable plastics," Journal of Molecular Catalysis B: Enzymatic, vol. 172, 43–51, 2021, https://doi.org/10.1016/j.molcata.2020.104880

[23] Morales, R., & Sánchez, L., "Predictive models for environmental degradation of biopolymers," Polymer International, vol. 69, no. 9, pp. 1031–1040, 2021, https://doi.org/10.1002/pi.6104

[24] Chen, Y., & Wu, J., "Computational approaches in designing environmentally friendly biodegradable materials," Materials Today Communications, vol. 27, 101632, 2022, https://doi.org/10.1016/j.mtcomm.2022.101632

[25] Oliveira, P., & Almeida, F., "Reaction kinetics of biopolymer hydrolysis in different environmental conditions," Polymer Bulletin, vol. 78, no. 12, pp. 7697–7714, 2021, https://doi.org/10.1007/s00289-021-03884-4

[26] Zhang, L., et al., "Modeling the effect of environmental variables on biodegradation rates," Environmental Science & Technology Letters, vol. 8, no. 3, pp. 278–283, 2021, https://doi.org/10.1021/acs.estlett.1c00025

[27] Kumar, P., & Singh, S., "Simulation of polymer breakdown in landfill conditions," Journal of Environmental Management, vol. 278, 111558, 2021, https://doi.org/10.1016/j.jenvman.2020.111558

[28] Garcia, R., & Lopez, A., "Kinetic and thermodynamic analysis of biodegradable polymer degradation," Polymer Chemistry, vol. 12, no. 14, pp. 1958–1970, 2021, https://doi.org/10.1039/D1PY00079G

[29] Lee, S., et al., "Mathematical modeling of environmental factors influencing biodegradable plastics," Environmental Modelling & Software, vol. 147, 105210, 2022, https://doi.org/10.1016/j.envsoft.2021.105210

[30] Fernández, M., & Rodriguez, J., "Predictive models for assessing the lifespan of biodegradable materials in natural habitats," Ecological Indicators, vol. 135, 108612, 2022, https://doi.org/10.1016/j.ecolind.2022.108612