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Review Paper

A brief review of efforts for sustainable Polymer Chemistry towards a Green Future

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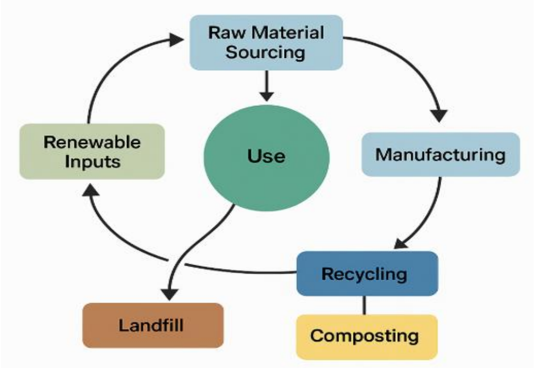
GRAPHICAL ABSTRACT



ABSTRACT

The protective coatings and flexible packaging industries play a pivotal role in modern society. They contribute to human health, safety, comfort, and economic progress. Initially, these materials were produced from naturally occurring components; however, they have since evolved into intricate compositions designed to fulfill various performance criteria. Currently, the majority of these materials are discarded in landfills, and their carbon content cannot be recovered or reused efficiently. In recent years, database statistics show a steady increase in research related to functional coatings, reflecting the growing interest in innovative and sustainable solutions. The global focus on reducing reliance on fossil fuel products and mitigating environmental impacts is accelerating efforts to integrate renewable resources into coating technologies. These technologies utilize bio-based raw materials, including biopolymers and natural oils, as well as biodegradable materials derived from microorganisms, plants, and animals. To address environmental concerns, leading coatings and packaging manufacturers have launched scientific and technical research to improve the sustainability of their products. Ongoing research focuses on the development of bio-derived materials, the adoption of energy-efficient manufacturing processes, the design of long-lasting products, and the use of sustainable and renewable resources. In addition, companies seek financial and competitive advantages through proactive internal initiatives. This highlights the urgent need for a circular economy model that overcomes current limitations in recycling and decomposition technologies. The authors stress the significance of comprehending society's tendency to prioritize and value sustainability, along with the financial and competitive advantages that may result from adopting proactive in-house efforts.

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1 Introduction

Protective coatings and flexible packaging sectors are essential in contemporary society, making substantial contributions to human safety, public health, comfort, and economic prosperity. Paints, sealants, and other coatings provide protection that extends the lifespan of houses, vehicles (cars, trains, trucks, and ships), buildings, industrial equipment, and other infrastructure [1, 2]. Modern packaging reduces food waste and enhances the safety of our diet. The polymer compounds used in packaging and coatings have undergone significant development in recent decades. Originally, these materials were manufactured from natural substances and had simple compositions. However, they have evolved into highly complex materials engineered to meet multiple performance requirements simultaneously. Leading producers of coatings and packaging, in collaboration with industry groups, have launched scientific and technological research to enhance sustainability. This includes developing bio-based, biodegradable, compostable, and recyclable materials [3].

These advances are being achieved by using fewer toxic materials, implementing energy-efficient production with lower volatile organic compound (VOC) emissions, and integrating sustainable, renewable energy sources. Some of these advances have resulted from regulatory constraints, but leading producers are innovating before more stringent regulatory restrictions are imposed. These companies recognize the financial and competitive benefits that can result from implementing proactive internal initiatives that prioritize sustainability [4, 5]. Most packaging and coatings are discarded in landfills, and the carbon in coated products, such as wood, cannot be recycled or reused. Due to their durability, current recycling and decomposition methods are ineffective, necessitating a circular approach for coatings, packaging, and related materials [6, 7]. Understanding the drivers of research in these sectors requires examining the interplay of consumer awareness, technological advancements in industry and academia, and government regulations. Companies spend significant resources to produce goods that align with customer preferences, and the success of new products often stems from their exceptional performance or cost-effectiveness. A key factor in advancing sustainable packaging and coatings through green chemistry is understanding societal valuation of sustainability [8]. Consumers view sustainability as an aspect of product performance; however, their willingness to pay a premium for sustainable products varies. While some consumers resist eco-friendly options, others perceive them as cost-saving opportunities through mechanisms such as carbon pricing or environmental incentives [9].

This perspective includes contributions from co-authors with varied experiences in both industry and academia. We identify key research areas in sustainability and green chemistry in academia and industry. Academic researchers are driven by opportunities to conduct impactful research that industry can adopt, fostering a sustainable future.

2 Coatings

Historically, binders for printing pigments and wood coatings, such as shellac coatings or linseed oil varnishes, were exclusively bio-based. As the chemical industry expanded, modified bio-based materials gained widespread use. Colophonium resins, modified cellulose esters, and alkyd resins remain prevalent today [10, 11]. However, most modern coatings are petrochemical-based. In the last decade, the industry has shifted toward replacing petrochemical building blocks with bio-based monomers derived from biotechnological processes, yielding novel coatings or precursors partially sourced from biological origins [12, 13, and 14]. Examples include a variety of isocyanates and bio-based polyols used in polyurethane applications, as well as widely available epoxy resins [15, 16]. However, the range of entirely bio-based coating materials remains somewhat restricted, and in many cases, such as phenolic resins or polyacrylates, there are no viable bio-based substitutes. Polysaccharide-based products, such as starch, are promising due to their abundance. However, their hydrophilic properties result in incompatibility with most synthetic polymers used in coatings [17, 18]. The challenge is to economically develop hydrophobic bio-sourced polymers suitable for aqueous dispersions with low viscosity, as dissolving polysaccharides in water often leads to high viscosity and processing difficulties. Total costs encompass not only material expenses but also costs for establishing a new supply chain infrastructure and reconfiguring coating lines. For rapid adoption, new materials must integrate seamlessly into existing systems without requiring significant modifications (Figure 1). Table 1 presents a comparison between bio-based and petrochemical coating materials.

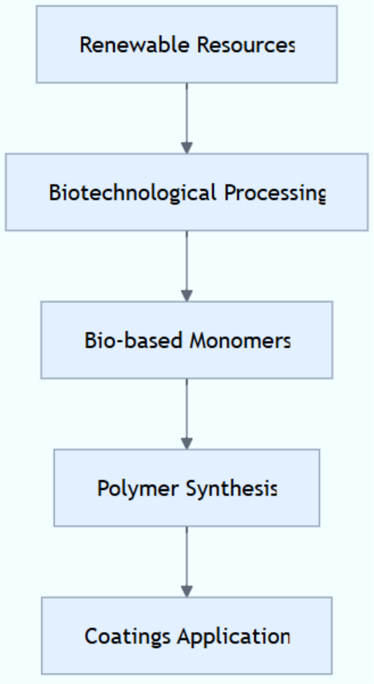

Figure 1 Bio-based Material Production Process

Table 1: Comparison of Bio-based vs. Petrochemical Coating Materials

Material Type	Source	Advantages	Challenges
Bio-based Polyols	Renewable (corn, starch)	Sustainable, reduced VOCs	Hydrophilic, high viscosity
Petrochemical Polyols	Fossil fuels	Established infrastructure, cost-effective	Non-renewable, environmental impact
Bio-based Epoxy Resins	Plant-based	Biodegradable potential	Limited availability, higher cost
Petrochemical Epoxy Resins	Fossil fuels	Wide applicability, durable	Non-sustainable, difficult to recycle

3 Flexible Packaging and Recycling of Intricate Materials

Although not classified as coatings in the traditional sense, flexible packaging materials possess several characteristics similar to coatings. They consist of thin, polymer-based layers engineered to protect contents from environmental exposure. They are available everywhere and are often designed for single use [19]. Modern flexible packaging, especially for food products, typically comprises multiple laminated layers. Each layer, usually a distinct polymer, serves a specific function, such as an oxygen barrier to maintain freshness. For example, potato chip bags often feature a base layer of polyethylene or polypropylene combined with additional functional layers possessing unique properties [20, 21].

To illustrate the composition and function of these layers, Table 2 summarizes key materials and their roles in flexible packaging.

Table 2. Flexible Packaging Layer Functions

Layer Material	Function	Challenges
Ethylene Vinyl Alcohol	Oxygen barrier	Poor mechanical properties
Polyethylene	Moisture barrier	Requires adhesive for lamination
Polyurethane Adhesive	Bonding	Hinders recycling

Ethylene vinyl alcohol (EVOH) is used as an oxygen barrier; however, its mechanical properties are suboptimal, and it performs poorly as a water barrier. To meet performance standards, it is typically combined with other films, such as polyethylene, using adhesives like polyurethane dispersions. While individual layers are potentially recyclable, the laminate as a whole is rarely recyclable on a commercial scale due to the strong adhesive bonds that make delamination and separation difficult. The development of innovative adhesives that can be deactivated by stimuli such as electric current, voltage, or light could significantly improve the recyclability of laminated packaging [22]. Figure 2 illustrates the proposed recycling process, emphasizing the role of delamination triggers.

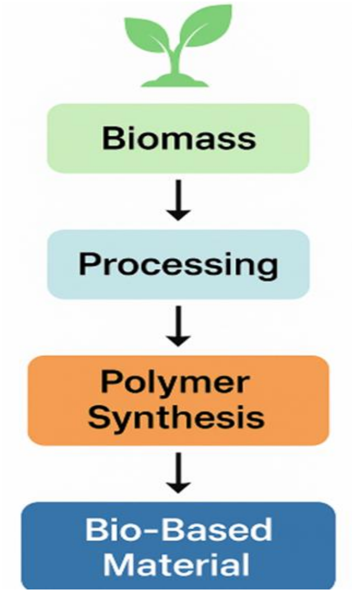

Figure 2. Bio-based Material Production Process

Any new recycling method must use a trigger with minimal environmental impact to ensure that the benefits outweigh non-recycling scenarios [23]. The use of solvents may initiate delamination; however, their environmental impact could outweigh the recycling benefits. Instead of developing new adhesive technologies, an alternative approach involves designing laminates that fulfill the required functions but can be easily separated at the end of their lifespan. Another method uses a single polymer with modified functionality and microstructure to perform multiple roles, enhancing recyclability [24, 25].

4 Novel Concepts and Strategies

A common method involves replacing petrochemical monomers with bio-based building blocks. This approach has enabled the successful production of binding resins for metal coatings using polyesters entirely sourced from renewable resources [26, 27]. Isosorbide, a bicyclic monomer, is crucial for achieving the high glass transition temperatures required in these applications. Smith et al. [28] demonstrated that alkyd resins can be entirely derived from bio-based materials by replacing phthalic and benzoic acids with imide structures synthesized from citric acid and amino acids. The same group showed that polycarbonates can be fully derived from renewable resources. By reacting limonene oxide with CO_2, followed by alcoholysis, binder resins with unique characteristics can be produced [29, 30]. Another key focus in green coatings is replacing polyurethanes made from diisocyanates, which rely on non-renewable resources, pose health and safety concerns, and create obstacles to producing fully biobased polyurethanes. Nonisocyanate polyurethanes, formed from the reaction between cyclic carbonates and amines to create hydroxy urethane linkages, offer a more environmentally friendly alternative [31]. Using limonene dicarbonate enables the production of these polymer resins from renewable resources [32]. However, limonene and other bio-derived materials often face cost challenges that limit their widespread use. Although versatile, limonene may be restricted to high-value products rather than commodity polymers [33]. Table 3 summarizes key novel coating technologies, highlighting their materials, advantages, and applications.

Table 3. Novel Coating Technologies

Technology	Base Material	Advantages	Applications
Developed Diffusion™	Polymer blends	Low VOC, rapid hardness	Aqueous coatings
Designed Hybridization	Latex + epoxy	Low VOC, extended pot-life	2K coatings
Bio-based Thermosets	Epoxidized sucrose soyate	Degradable, sustainable	Flame-retardant coatings

a novel coating was developed using carbon-dioxide–switchable polymers that are insoluble in neutral pH water but dissolve in carbonated water [34]. Upon application, the polymer transitions from hydrophilic to hydrophobic as CO_2 and water evaporate, forming a transparent, water-resistant, and continuous coating. These coatings combine the advantages of being VOC-free, similar to water-based systems, while eliminating the need for particle coalescence and offering the potential to replace solvent-based coatings. Properly modified, bio-sourced nanoparticles can act as efficient pickering stabilizers, potentially replacing traditional surfactants [35, 36]. Recent studies demonstrate bio-surfactants' effectiveness in emulsion polymerization. Research continues to develop novel techniques for incorporating starch nanoparticles into emulsified polymers (latexes) to increase their bio-content [37, 38]. Recent reports highlight flame-resistant multilayer coatings using chitosan instead of bromine-containing compounds. To soften the polymer, VOCs are added, which incorporate into the polymer latex coatings and allow film formation. After application, the coatings harden, becoming tack-free and durable as VOCs evaporate during drying. To maintain the film composition (MFFT) at low temperature and its properties related to rigidity, such as printing, block resistance, and dirt pick-up, there is an urgent need to reduce VOCs [39].

Dow's Developed Diffusion™ technology provides a novel solution to reduce VOCs while ensuring rapid hardness development and low-temperature film formation. This technology combines two polymers and adds a small amount of a specially designed soft polymer (DD) to a dominant a high-glass-transition-temperature (T_g) polymer (Polymer A). This enhances initial property development. The polymers (Polymer A and DD) are selected so that the coalescent partitions into Polymer A when wet. Film formation triggers a shift in the coalescent distribution between the two polymers. Transferring the coalescent to Polymer DD facilitates its efficient removal from Polymer A, accelerating coating property development [40]. Figure 3 illustrates the Developed Diffusion™ process, showing the interaction of polymers and coalescents for low-VOC coating formation.

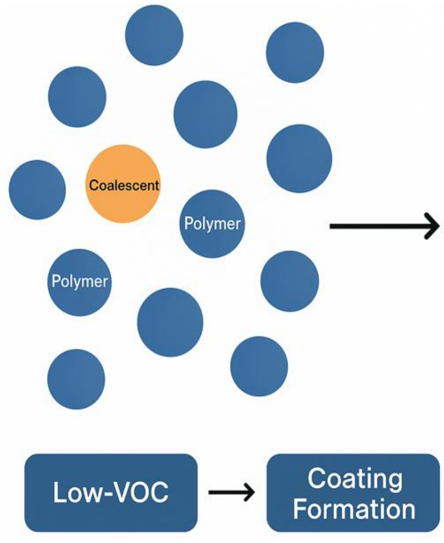

Figure 3. Developed Diffusion™ Process

The designed hybridization method marks a significant advance in developing novel aqueous coatings, enabling the creation of both thermoplastic and deformable latex polymers. It involves initially producing a latex particle template via free radical emulsion polymerization of vinyl monomers. Subsequently, the particles are enlarged by absorbing reactive molecules that have suitable properties for further reactions. Experiments tested the combination of large-molecule latex polymer compounds with liquid epoxy resins in two-component (2K) coating applications. The resulting coating's properties depend on the glass transition temperature and composition of the latex polymer, as well as the type and quantity of epoxy resin and curing agent used [41].

In hybridized latex systems, liquid epoxy functions as a coalescent, enabling film formation by the latex polymer, which simultaneously serves as a host for controlled epoxy dispersion. During curing with external hardeners, phase separation occurs between the epoxy and the latex host, thereby restoring the original hardness of the latex polymer. Such hybridization methods yield formulations with extended pot life, rapid hardness development, and near-zero VOC emissions, producing dry coating properties that are otherwise difficult to achieve [42]. In parallel, bio-based and degradable thermosets have been developed from epoxidized sucrose soyate, derived through the epoxidation of sucrose ester resins from soybean oil fatty acids. Crosslinking can be achieved using carboxylic acid–containing components from natural sources, such as fruit juices. Incremental advances have resulted in thermosets with favorable mechanical properties and, notably, the capacity to degrade under corrosive conditions or at elevated temperatures. More broadly, materials designed with a "switch" to trigger biodegradation or enable recycling at end-of-life hold significant potential to transform the coatings industry [43, 44].

5 Conclusion

The primary objective is to develop coating materials that can be efficiently reclaimed and either reused for their original function or repurposed as raw materials in new industrial applications. While significant progress has been achieved, future research must account for several critical factors. Before large-scale implementation, both the environmental and economic impacts of novel coatings require thorough evaluation. Life cycle assessments are essential to identify products with net positive impacts, eliminate those with adverse effects, and quantify expected reductions in greenhouse gas emissions and landfill waste. In addition, broader ecological consequences must also be carefully considered.

Research on this topic is limited in the published literature, with existing studies primarily focusing on specific compounds. Additionally, developing distinct coatings with tunable properties can face challenges when integrated into multi-layer laminates. The synergistic interactions of multiple coatings are often neglected, despite available methods in the literature for studying them. It is critical to validate standard coating application formulations to ensure efficient delamination and material recovery. Moreover, a thorough assessment of the policy implications of these products is essential. Without policy mechanisms, such as carbon pricing, that recognize reductions in greenhouse gas emissions, neither producers nor consumers may benefit. Figure 4 illustrates a circular economy model for coatings, emphasizing reclamation and repurposing.

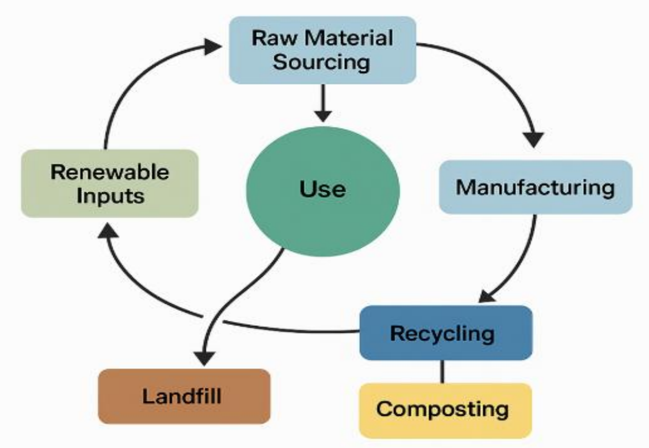

Figure 4. Circular Economy Model for Coatings

References

1. Li, Q., Long, R., Chen, H., Empirical Study of the Willingness of Consumers to Purchase Low-carbon Products by Considering Carbon Labels: A Case Study, *Journal of Cleaner Production*, 161, 1237-1250, 2017.
2. Ali, Zainab A., Alaa Karem Niamah, and Hannosh Widad Salih. Isolation, preparation, and characterization of polylactic acid film reinforced with nano silica. Journal of Physics: Conference Series. Vol. 2063. No. 1.p. 012028. *IOP Publishing*, 2021.
3. Cunningham, M. F., Campbell, J. D., Fu, Z., Bohling, J., Leroux, J. G., Mabee, W., Robert, T., Future Green Chemistry and Sustainability Needs in Polymeric Coatings, *Green Chemistry*, 21(18), 4919-4926, 2019.
4. Shao, J., Ünal, E., What Do Consumers Value More in Green Purchasing? Assessing the Sustainability Practices from Demand Side of Business, *Journal of Cleaner Production*, 209, 1473-1483, 2019.
5. Cheng, H. N., Gross, R. A., Sustainability and Green Polymer Chemistry— an Overview, Sustainability & Green Polymer Chemistry, 1, 1-11, 2020.
6. Ayre, D., Technology Advancing Polymers and Polymer Composites towards Sustainability: A Review, Current Opinion in Green and Sustainable Chemistry, 13, 108-112, 2018.
7. Mohanty, A. K., Wu, F., Mincheva, R., Hakkarainen, M., Raquez, J. M., Mielewski, D. F., Misra, M., Sustainable Polymers, *Nature Reviews Methods Primers*, 2(1), 46, 2022.
8. Moustafa, H., Youssef, A. M., Darwish, N. A., Abou-Kandil, A. I., Eco-friendly Polymer Composites for Green Packaging: Future Vision and Challenges, Composites Part B: Engineering, 172, 16-25, 2019.
9. Getzler, Y. D., Mathers, R. T., Sustainable Polymers: Our Evolving Understanding, Accounts of Chemical Research, 55(14), 1869-1878, 2022.

10. Izdebska-Podsiadły, J., Thomas, S., Printing on Polymers: Fundamentals and Applications, *William Andrew*, 2015.
11. Jones, F. N., Nichols, M. E., Pappas, S. P., Organic Coatings: Science and Technology, John Wiley & Sons, 2017.
12. Delidovich, I., Hausoul, P. J., Deng, L., Pfützenreuter, R., Rose, M., Palkovits, R., Alternative Monomers Based on Lignocellulose and Their Use for Polymer Production, *Chemical Reviews*, 116(3), 1540-1599, 2016.
13. Gandini, A., Lacerda, T. M., Carvalho, A. J., Trovatti, E., Progress of Polymers from Renewable Resources: Furans, Vegetable Oils, and Polysaccharides, *Chemical Reviews*, 116(3), 1637-1669, 2016.
14. Tremblay-Parrado, K. K., Synthesis by Click Chemistry of Bio-based Polyurethane Networks with Advanced Properties, Doctoral Dissertation, Université de Strasbourg, 2020.
15. Tenorio-Alfonso, A., Sánchez, M. C., Franco, J. M., A Review of the Sustainable Approaches in the Production of Bio-based Polyurethanes and Their Applications in the Adhesive Field, *Journal of Polymers and the Environment*, 28, 749-774, 2020.
16. Liu, J., Zhang, L., Shun, W., Dai, J., Peng, Y., Liu, X., Recent Development on Bio-based Thermosetting Resins, *Journal of Polymer Science*, 59(14), 1474-1490, 2021.
17. Marques, S., Moreno, A. D., Ballesteros, M., Gírio, F., Starch Biomass for Biofuels, Biomaterials, and Chemicals, Biomass and Green Chemistry: Building a Renewable Pathway, 69-94, 2018.
18. Makroo, H. A., Naqash, S., Saxena, J., Sharma, S., Majid, D., Dar, B. N., Recovery and Characteristics of Starches from Unconventional Sources and Their Potential Applications: A Review, *Applied Food Research*, 1(1), 100001, 2021.
19. Lindström, T., Österberg, F., Evolution of Bio-based and Nanotechnology Packaging–A Review, Nordic Pulp & Paper Research Journal, 35(4), 491-515, 2020.
20. Ali, Zainab A., Production of polylactic acid from lactic acid produced by a local isolate of lactic acid bacteria and its use in the preparation of nano film and its application in Barhi packaging. PhD. Thesis, *University of Basrah.Iraq*, 2021.
21. Krochta, J. M., Food Packaging, Handbook of Food Engineering, 1031-1124, 2018.
22. Cunningham, M. F., Campbell, J. D., Fu, Z., Bohling, J., Leroux, J. G., Mabee, W., Robert, T., Future Green Chemistry and Sustainability Needs in Polymeric Coatings, *Green Chemistry*, 21(18), 4919-4926, 2019.
23. KAREM, Alyaa Abdul Hasan Abdul; Sweah, Zainab J.; Malik, Fatima H. Production of Alum from Aluminium Drink Cans Waste for Water Treatment. 2023.
24. Park, J., Advanced Topology Optimization Techniques for Engineering and Biomedical Problems, *The Ohio State University*, 2018.
25. Khalid, M. Y., Arif, Z. U., Ahmed, W., Arshad, H., Recent Trends in Recycling and Reusing Techniques of Different Plastic Polymers and Their Composite Materials, *Sustainable Materials and Technologies*, 31, e00382, 2022.
26. Lomelí-Rodríguez, M., Corpas-Martínez, J. R., Willis, S., Mulholland, R., Lopez-Sanchez, J. A., Synthesis and Characterization of Renewable Polyester Coil Coatings from Biomass-derived Isosorbide, FDCA, 1,5-Pentanediol, Succinic Acid, and 1,3-Propanediol, Polymers, 10(6), 600, 2018.
27. Hevus, I., Ricapito, N. G., Tymoshenko, S., Raja, S. N., Webster, D. C., Bio-based Carboxylic Acids as Components of Sustainable and High-performance Coating Systems, *ACS Sustainable Chemistry & Engineering*, 8(14), 5750-5762, 2020.
28. Koning, C., Lansbergen, A., Koldijk, F., Hendriks, H., Papegaaij, A., Smabers, R., Herrema, J., Novel Renewable Alkyd Resins Based on Imide Structures, *Journal of Coatings Technology and Research*, 14(4), 783-789, 2017.
29. Bendiabdallah, C., Reguieg, F., Belbachir, M., Synthesis of Bio-based Poly Limonene Oxide with Green Catalyst, *Current Chemistry Letters*, 10(3), 271-280, 2021.
30. Li, C., Johansson, M., Buijsen, P., Dijkstra, G., Sablong, R. J., Koning, C. E., Limonene-derived Polycarbonates as Bio-based UV-curable (Powder) Coating Resins, Progress in Organic Coatings, 151, 106073, 2021.
31. Huy, N. G., Non-isocyanate Polyurethane Towards Green Chemistry, *Journal TBD*, 2024.
32. Mouren, A., Avérous, L., Sustainable Cycloaliphatic Polyurethanes: From Synthesis to Applications, *Chemical Society Reviews*, 52(1), 277-317, 2023.
33. Li, S., Rong, L., Wang, S., Liu, S., Lu, Z., Miao, L., Yu, A., Enhanced Limonene Production by Metabolically Engineered Yarrowia Lipolytica from Cheap Carbon Sources, *Chemical Engineering Science*, 249, 117342, 2022.
34. Ho, J., Mudraboyina, B., Spence-Elder, C., Resendes, R., Cunningham, M. F., Jessop, P. G., Water-borne Coatings That Share the Mechanism of Action of Oil-based Coatings, *Green Chemistry*, 20(8), 1899-1905, 2018.
35. Pei, X., Tan, Y., Xu, K., Liu, C., Lu, C., Wang, P., Pickering Polymerization of Styrene Stabilized by Starch-based Nanospheres, *Polymer Chemistry*, 7(19), 3325-3333, 2016.
36. Saelices, C. J., Save, M., Capron, I., Synthesis of Latex Stabilized by Unmodified Cellulose Nanocrystals: The Effect of Monomers on Particle Size, *Polymer Chemistry*, 10(6), 727-737, 2019.
37. Zhang, Y., Cunningham, M. F., Smeets, N. M., Dubé, M. A., Increasing Starch Nanoparticle Content in Emulsion Polymer Latexes, *Industrial & Engineering Chemistry Research*, 58(46), 20987-20995, 2019.
38. Gabriel, V. A., Sustainable Polymer Reaction Engineering: Towards Fully Renewable Pressure-Sensitive Adhesives, Doctoral Dissertation, *Université d'Ottawa/University of Ottaw*a, 2022.
39. Lazar, S., Garcia-Valdez, O., Kennedy, E., Champagne, P., Cunningham, M., Grunlan, J., Crosslinkable-chitosan-enabled Moisture-resistant Multilayer Gas Barrier Thin Film, Macromolecular Rapid Communications, 40(6), 1800853, 2019.
40. Fu, Z., Hejl, A., Swartz, A., Beshah, K., Dombrowski, G., Film Formation Through Designed Diffusion Technology, Protective Coatings: Film Formation and Properties, 153-168, 2017.
41. Doagou-Rad, S., Islam, A., Merca, T. D., An Application-oriented Roadmap to Select Polymeric Nanocomposites for Advanced Applications: A Review, *Polymer Composites*, 41(4), 1153-1189, 2020.
42. Olabode, O. E., Ajewole, T. O., Okakwu, I. K., Alayande, A. S., Akinyele, D. O., Hybrid Power Systems for Off-grid Locations: A Comprehensive Review of Design Technologies, Applications and Future Trends, *Scientific African*, 13, e00884, 2021.
43. Shen, M., Sustainable and Degradable Epoxy Resins Containing Multifunctional Bio-based Components, *Journal TBD*, 2021.
44. Wang, X., Nabipour, H., Kan, Y. C., Song, L., Hu, Y., A Fully Bio-based, Anti-flammable and Non-toxic Epoxy Thermosetting Network for Flame-retardant Coating Applications, *Progress in Organic Coatings*, 172, 107095, 2022.