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Bio-based Oligomers: Progress, Applications and Future Perspectives

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ABSTRACT

In response to growing environmental concerns, the coatings industry is undergoing a significant shift towards sustainability. Key technologies driving this transformation include water-borne coatings, radiation-curable solutions and high-solid powder coatings. Additionally, bio-based materials sourced from biomass or biomass-dependent processes are gaining prominence as environmentally friendly alternatives to fossil fuel-based materials. These materials offer versatility through chemical modifications and enable advanced curing techniques while enhancing the overall sustainability profile of coatings. This study provides a comprehensive short review of recent research efforts focused on developing coatings with high bio-renewable content. It examines the progress made in this area, explores various applications and offers insights into future perspectives. By synthesizing and analyzing the latest advancements, this study contributes to the ongoing discourse surrounding sustainable coatings and highlights opportunities for further innovation in the field.

Keywords: Growing environmental concerns; Water-borne coatings; Radiation-curable solutions; High-solid powder coatings; Bio-renewable content

INTRODUCTION

The chemical industry is increasingly embracing renewable and bio-based polymers to replace petroleum-based counterparts, driven by concerns over environmental sustainability, economic feasibility and effective waste management [1]. This shift responds to worries about declining fossil fuel reserves, environmental impacts and the prevalence of Volatile Organic Compounds (VOCs), prompting exploration of sustainable raw materials [2,3]. Integrating "green" materials in coatings signifies a move towards sustainable synthesis, meeting the demand for economically viable products [4,5]. The U.S. Department of Energy aims for 50% of chemical building blocks to come from plant-based sources by 2050, propelling the coatings industry to adopt a combination of renewable materials and green technologies like waterborne coatings and UV cures to reduce VOC emissions [6,7]. Waterborne coatings, for instance, offer benefits such as reduced air pollution and lower energy consumption, despite challenges like longer drying times and adhesion issues [8-10].

UV-curing technology is praised for its environmental friendliness and efficiency, but sustainability demands renewable coating components, given the reliance on fossil-based prepolymers [11,12]. Although UV curing offers

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rapid, VOC-free polymerization, challenges such as shrinkage and adhesion issues persist [13,14]. This study offers a comprehensive short review of recent research endeavors aimed at developing bio-based oligomers for diverse applications, providing valuable insights into the ongoing efforts to advance sustainable coatings technology.

LITERATURE REVIEW

Bio-based oligomers/binders

Binders serve as the backbone of coating formulations, dictating their properties, applications, curing methods and sustainability. The quest for environmentally friendly coatings necessitates the development of sustainable binders, prompting extensive efforts to incorporate high levels of bio-renewable materials. For example, a variety of bio-based chemicals, including itaconic acid, tartaric acid, isosorbide, vanillin, cyclodextrin and lignin, have found widespread use in modifying epoxy resins [15,16]. In a recent review, Lopes et al., highlighted significant studies from recent years focused on technologies for stabilizing lignin, a common raw material for synthesizing bio-based oligomers. These technologies aim to achieve high depolymerization yields and include approaches such as hydrogenation (RCF), alkoxylation (Organosolv) and acetal formation to stabilize lignin depolymerization products and prevent condensation reactions. Such lignin-first approaches are at the forefront of research, along with strategies for functionalizing lignin monomers into valuable aromatic platform chemicals, such as aromatic amines [17]. Similarly, Ali et al., compiled data over the past five years on photo-curable polyurethanes categorized based on solvent and acrylate components. Their comprehensive study encompassed various parameters including tensile strength, hardness, flexibility, hydrophobicity/hydrophilicity, solvent resistance, storage Young's modulus, shape recovery, viscosity, curing kinetics and thermal stability for different bio-based compositions [18]. Despite advancements, challenges like brittleness, slow drying and inadequate adhesion persist in bio-based coatings, necessitating innovative solutions [19]. Furthermore, the integration of organic-inorganic hybrid crosslinkers has emerged as a promising strategy for enhancing the mechanical strength and anticorrosive properties of coatings. This approach has garnered attention for its potential to improve coating performance while maintaining eco-friendly credentials [20]. Recent studies have focused on bio-based organic-inorganic hybrid UV-curable coatings, showcasing self-cleaning properties and practical applications. Additionally, researchers are exploring the addition of Tetraethyl Orthosilicate (TEOS) into Non-Isocyanate Polyurethane (NIPU) coatings to bolster corrosion resistance. Novel approaches in resin synthesis include the development of water-based organic-inorganic nano-hybrid resins through *in-situ* hydrolysis-condensation reactions. At the forefront of this research landscape, our team at the Coating Research Institute, Eastern Michigan University, is actively engaged in advancing sustainable high-solid organic-inorganic hybrid systems. Leveraging innovative curing capabilities and a focus on renewable materials, our efforts aim to drive forward the development of coatings that meet the dual objectives of performance and environmental responsibility.

DISCUSSION

Applications

Bio-based oligomers have emerged as versatile components for developing coatings across a wide spectrum of applications. Notably, efforts to create environmentally friendly wood coatings have been extensively reviewed by Calovi et al. This exploration delves into the potential of essential oils, vegetable oils and bio-based polymers in crafting durable and eco-friendly coating matrices. Additionally, the review addresses strategies for enhancing weathering resistance and combating biological decay through the application of natural compounds and extracts, assessing their efficacy as alternatives to traditional chemical preservatives and identifying promising candidates. In another study, Naiker et al., examined research focused on developing bio-based materials for formulating flame retardant coatings. Harnessing natural resources, such as phosphorus-based flame-retardant systems, offers a pathway to creating fire-safe coatings. Moreover, the study underscores the synergistic effects of incorporating elements like nitrogen, silicon, boron and sulfur alongside phosphorus, highlighting the potential of bio-based phosphorus-containing flame-retardant systems. Furthermore, efforts to design durable flame-retardant epoxy coatings with

superior mechanical properties, thermal resistance and transparency have gained traction. Introducing hyperbranched phosphorus-containing, bio-based flame retardants presents a promising avenue for achieving these objectives. The integration of bio-based materials with UV-curable technology represents another notable endeavor, particularly in the industrial, cosmetic and beauty industries. However, the application of bio-based oligomers extends beyond these examples, with ongoing research aimed at exploring their utilization across various sectors and further enhancing their sustainability.

Future prospectives

The future of bio-based oligomers in coatings appears promising as industries increasingly prioritize sustainability. Ongoing research aims to optimize renewable resources like essential oils and bio-based polymers, ensuring coatings are not only durable but also environmentally friendly. This emphasis on eco-friendliness extends to specialized applications such as wood and flame-retardant coatings, where natural compounds are utilized to combat environmental hazards effectively. Moreover, integrating bio-based oligomers with advanced technologies such as UV-curable coatings and nanotechnology offers exciting prospects for enhancing coating performance across various industries. By leveraging the synergistic effects of bio-based materials with cutting-edge methodologies, coatings with superior mechanical properties, enhanced thermal resistance and improved transparency can be achieved. This integration not only improves coating performance but also underscores the industry's commitment to sustainability. Looking ahead, collaboration between academia and industry will be crucial for driving the development and adoption of bio-based oligomers in coatings. Together, stakeholders can accelerate innovation, bringing sustainable, high-performance coating solutions to market more efficiently. As bio-based oligomers continue to evolve, they are poised to emerge as a cornerstone of the coatings industry, offering eco-friendly alternatives that meet the demands of tomorrow's world.

CONCLUSION

The transition toward renewable and bio-based polymers in the coatings industry is a critical response to the growing environmental concerns associated with petroleum-based materials. As this review highlights, ongoing research and innovation in bio-based oligomers are laying the groundwork for a more sustainable future in coatings technology. The integration of renewable resources such as lignin, essential oils and other bio-derived materials is paving the way for the development of high-performance coatings that meet both economic and ecological standards.

Despite the progress made in enhancing the properties and applications of bio-based oligomers, challenges such as brittleness, drying times and adhesion issues remain prevalent. However, the exploration of organic-inorganic hybrid systems and advanced curing techniques, such as UV curing, presents promising pathways to overcome these limitations while ensuring environmental sustainability.

As industries continue to prioritize eco-friendly practices, collaboration between researchers, manufacturers and policymakers will be vital in accelerating the adoption of bio-based solutions. By embracing innovative methodologies and leveraging natural resources, the coatings industry can fulfill its commitment to sustainability while delivering durable, effective products. The future of coatings lies in the successful integration of bio-based oligomers, ultimately contributing to a greener, more sustainable chemical landscape that aligns with both consumer demand and regulatory expectations.

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