**Green Chemistry Strategies to Enhance the Thermal Stability of PVC: A State-of-the-Art Overview on Plant Oil-Derived Stabilizers: Mini-review Article**

**Abstract**:

 Polyvinyl chloride (PVC) finds use in various industries due to its versatility but is not thermostable, serving as a barrier to causing degradation and release of hydrochloric acid (HCl) under heat stress conditions. Lead and organotin compounds have traditionally been used for stabilizer purpose to discourage such degradation but pose serious ecological as well as health risks. As a counter measure, bio-based stabilizers from plant oils have become popular as a green and sustainable alternative. This review looks back at recent developments in plant oil-based stabilizers for PVC, focusing on the mechanisms of stabilization, sustainability, and cost-effectiveness. We review plant oils such as tung oil, castor oil, and soybean oil, with their ability to improve the thermal stability of PVC. Although promising outcomes, there are still challenges to overcome, such as compatibility with the PVC matrix and scalability. This review presents a comprehensive summary of the current status of plant oil-based stabilizers and provides insights into directions for future research.

**Keywords: Green Chemistry, Environmental Impact, Biodegradable Stabilizers, PVC Degradation**

Introduction:

 Polyvinyl chloride (PVC) is the most widely utilized thermoplastic globally due to ease of processing, low cost, and flexibility. It is applied from medical equipment to building materials, and hence it is a significant material employed in current industries (Grim, 2017).However, despite widespread application, PVC is thermally unstable due to the stability issues of its carbon-chlorine bonds.PVC breaks down when heated, and it releases hydrochloric acid (HCl), which also contributes to polymer breakdown (Yu et al., 2015). Release of HCl triggers a series of chemical reactions that produce discoloration, loss of mechanical properties, and degradation of PVC products with time (Tamang et al., 2024; Tian et al., 2024). To avoid these conditions, stabilizers are incorporated in PVC formulations. The stabilizers reverse the released HCl as a result of degradation, suppress free radical formation, as well as polymer chain scission, and in the process maintain the material in its integrity form (Gardi et al., 2024). The reason why the traditional metal-based stabilizers such as lead and organotin compounds have been traditionally utilized for this is that they inhibit thermal degradation (Genua et al., 2025). However, their utilization has been blamed on their harmful effects on the environment and human health. Lead and organotin compounds can be environmentally persistent and possess significant hazards to ecosystems and human health (Zhang et al., 2024). In attempts to surmount such limitations, there has been a quest for more environmentally friendly alternatives, and stabilizers based on plant oils have emerged as a sufficient option. Plant oils, being free from toxicity, renewable, and biodegradable, offer a potentially good alternative to PVC's thermal stability with less health and environmental hazard (Siddiqui et al., 2023). Tung oil, castor oil, and soybean oil bio-stabilizers, among others, have also demonstrated tremendous capability to stabilize PVC without exhibiting the undesirable side effect of traditional stabilizers (Putrawan & Rahmawati, 2025). Current studies have focused on the modes of action of stabilizers of plant oil origin. Stabilizers of plant oil origin have been shown to effectively inhibit thermal degradation of PVC by means of free radical stabilization, neutralization of HCl, and enhancement of polymer heat resistance (Ye et al., 2019). In addition, plant oil stabilizers are cheaper and easily accessible compared to the conventional stabilizers, providing an economic benefit to use (Tamang et al., 2022). This has increased the research amount to further develop their performance for industrial use. This article will overview recent developments in plant oil-based PVC stabilizers, their action mechanism, efficacy, and potential environmental and economic advantages they can ensure. We will also refer to some disadvantages of applying them and sketch directions for future research in this promising area (Putrawan et al., 2022).

Thermal Degradation of PVC and Stabilization Needs Polyvinyl chloride (PVC) thermal degradation is caused primarily by the instability of its carbon-chlorine bonds under high temperatures. PVC degradation releases hydrochloric acid (HCl), an autocatalyst which promotes further decomposition (Chaochanchaikul et al., 2011; Sombatsompop et al., 2008). PVC stabilizers neutralize HCl, which prevents chain scission and free radical generation, and preserves structural integrity (Sombatsompop et al., 2009). Vegetable oil-based bio-stabilizers are becoming more popular due to their non-toxicity, biodegradability, and renewability (Kawee, 2025). Plant oil stabilizers were found to display outstanding potential to inhibit thermal degradation of PVC by processes like cross-linking reaction, metal complexation, and free radical entrapment. Collectively, these processes give the PVC improved thermal stability along with reducing its degradation rate, hence presenting a more eco-friendly alternative compared to conventional stabilizers (Jia et al., 2019).

### Types of Plant Oils Used for PVC Stabilization:

#### 1. Tung Oil (Vernicia fordii):

Tung oil, obtained from tung seeds, has been used because of its excellent stabilization of PVC. It is due to the presence of a high percentage of eleostearic acid-a conjugated fatty acid-in it. Cross-linking of the polymer matrix by the conjugated double bonds of eleostearic acid traps free radicals and thus avoids further degradation of PVC. The current work has confirmed that stabilizers obtained from tung oil, such as those of calcium and zinc salts of eleostearic acid-derived polycarboxylic acids, are more thermostable for the long term compared to the conventional calcium-zinc stearate stabilizers. These tung oil-derived stabilizers not only delay the initiation of thermal degradation but also decelerate discoloration and extend the process window of PVC, indeed curing such issues as "zinc burning" inherent with traditional stabilizers (Montoya, 2024). Studies indicate that tung oil-based stabilizers can increase the thermal degradation onset temperature by up to 25% relative to conventional calcium-zinc systems (Li et al., 2018). This makes them in the race to be considered sustainable, very effective alternatives for PVC stabilization.

**Figure 1: Thermal Degradation Comparison of PVC with Different Stabilizers**

#### 2. Castor Oil and Ricinoleic Acid: Castor oil derived from Ricinus communis consists of ricinoleic acid-a fatty acid with hydroxyl and carboxyl functional groups. As a result of the functional groups, the derivatives of castor oil are able to chelate metal ions such as calcium and zinc capable of neutralizing hydrochloric acid (HCl) formed during the thermal degradation of PVC and thus enhancing its thermal stability. These results have demonstrated that castor oil plasticizers and stabilizers significantly improve the thermal and mechanical properties of PVC. For instance, epoxy acetylated castor oil (EACO) and other epoxidations or esterifications have enhanced tensile strength, thermal stability, and migration resistance when compared to conventional stabilizers and plasticizers (Jia et al., 2017).

#### Thermal stability tests validate that castor oil-based stabilizers were able to reduce the rate of thermal degradation of PVC by up to 20% compared to traditional systems, with certain compositions also suppressing migration and further enhancing flame retardancy (Jia et al., 2019). Structurally modified castor oil derivatives with synergistic flame retardant properties or epoxide groups have been shown to enhance the onset temperature for PVC degradation as well as enhance the whiteness retention of the material under thermal aging (Zhang et al., 2022; Wang et al., 2022)

#### .

**Figure 2: Comparison of PVC Stabilized with Castor Oil and Other Stabilizers**

#### 3. Soybean Oil-Based Stabilizers:

### Soybean oil, which is rich in unsaturated fatty acids, has been discovered to enhance the thermal stability of polyvinyl chloride (PVC) when used as a stabilizer. Soybean oil derivatives that are chemically modified, such as epoxidized soybean oil (ESBO), have been discovered to be extremely effective at reducing the discoloration rate and delaying the onset of thermal degradation in PVC. The unsaturated and epoxidized functional groups in the derivatives of soybean oil help to suppress the release of hydrochloric acid (HCl) and stabilize the polymer chains, thereby leading to improved thermal and mechanical properties. Recent studies have shown 20% improvement of the onset temperature for thermal degradation and 15% less discoloration on the use of soybean oil-based stabilizers compared to conventional counterparts. For example, Chen & Wang. (2020) demonstrated that the derivatives of modified soybean oil significantly improved PVC's thermal degradation onset and reduced discoloration, confirming their effectiveness as green stabilizers.

**Figure 3: Effect of Soybean Oil-Based Stabilizers on PVC Thermal Properties**

### Mechanisms of Stabilization by Plant Oil Derivatives:

Polyvinyl chloride (PVC) stabilization with derivatives of plant oils takes place through various mechanisms, which are quite well documented.

Cross-Linking Reactions:

Conjugated fatty acids present in certain plant oils, such as tung oil, have the ability to react with PVC chains through Diels-Alder reactions. This forms stable cross-linked networks within the polymer matrix that trap free radicals and prevent further PVC degradation. This cross-linking enhances both the mechanical properties and the thermal stability of the material (Jia et al., 2023; Wang et al., 2022).

Metal Complexation:

Functional groups (such as hydroxyl and carboxyl groups) of plant oil derivatives can complex metal ions such as calcium and zinc. These complexes neutralize hydrochloric acid (HCl) released during PVC degradation and thus reduce chain scission, thereby improving the long-term thermal stability of the polymer (Li et al., 2017).

Free Radical Scavenging:

### Derivatives of plant oils, particularly those with epoxidized or unsaturated moieties, are capable of behaving as free radical scavengers. By reacting with and deactivating reactive radical species that are formed during thermal breakdown, these derivatives restrict the propagation of degradation reactions and increase the service lifespan of PVC products (Jia et al., 2019; Wang et al., 2023).

### Environmental and Economic Considerations:

### Plant oil-derived stabilizers are very environmentally friendly for the processing of PVC since they are biodegradable and renewable resource-based. Compared with traditional metal-based stabilizers, which can persist in the environment and exert toxicity and heavy metal accumulation, plant oil-derived stabilizers are more degradable and therefore minimize the environmental footprint of PVC products. For example, stabilizers based on tung oil and epoxidized soybean oil are derived from renewable resources and represent environmentally friendly alternatives ensuring safer production and better applications in various industries (Wiesinger et al., 2024).

### In addition to that, vegetable oils such as soybean and castor oil are easily accessible, inexpensive, and abundant, which can be utilized as an inexpensive and green alternative to conventional stabilizers. Other than solving the issue of environmental safety, they also fulfill industrial trends in resource conservation and green chemistry (Starnes et al.,2006 ; Silva et al., 2021). The application of plant oil-based stabilizers enables the plastics sector to reduce the application of toxic additives, produce safer products, and achieve sustainable development across the PVC lifecycle (Liu et al., 2012).

**Figure 4: Comparison of Environmental Impact of Different Stabilizers**

### Comparison with Conventional Stabilizers:

### Repeatedly, research has confirmed that oil-derived stabilizers from plants, particularly tung oil-based, excel over conventional stabilizers such as calcium-zinc and lead-type systems in both thermal stability and environmental friendliness (Shah & Shertukde, 2003; Chen et al., 2017; Fadli et al., 2022). Tung oil-based stabilizers have been found to have unique advantages in slowing the initiation of thermal degradative reactions, reducing coloration, and enhancing the mechanical properties of PVC. For example, new generation tung oil-based stabilizers such as Ph-T and Ph-TO not only improve the heat stability of PVC but also enlarge the processing window, minimize zinc burning, and offer the benefit of dual stabilization and plasticization, making them highly appropriate for severe applications including medical and industrial products (Montoya, 2024; Zhu et al., 2023; Shubbar et al., 2023). Despite these advances, there are a few challenges with the broader application of plant oil-based stabilizers:

### Compatibility with PVC Matrix: Some plant oil derivatives may be less compatible with the PVC polymer matrix, reducing their stabilization efficiency. Compatibility and interaction with PVC in an appropriate manner is needed to attain maximum stabilization efficiency (Li et al., 2020).

### Long-Term Stability: While plant oil-based stabilizers have shown significant potential in controlled laboratory settings, further research would be needed to assess their long-term stability, especially in cases involving outdoor usage where UV irradiation and oxygen exposure could work to accelerate degradation (Hasan et al., 2023; Hassan et al., 2019; Wang et al., 2023).

### Scalability and Cost: Although crude plant oils are inexpensive and readily available, the cost and challenge of industrial-scale synthesis of modified derivatives may be daunting. Cost-effective synthesis pathways development and process optimization are key to commercial viability of such stabilizers (Fadli et al., 2022; Zhang et al., 2022).

### Future research directions should involve increasing the compatibility of PVC with plant oil-based stabilizers, investigating their long-term performance in real applications, and refining the manufacturing process to reduce costs and facilitate large-scale application. Further research on this topic is expected to continue enhancing PVC product sustainability and performance, facilitating the transition to greener materials for the plastics sector.

**Figure 5: Comparative Analysis of PVC Stabilized with Tung Oil Derivatives and Conventional Stabilizers**

### Conclusion:

Plant oil-derived stabilizers are a feasible and eco-friendly substitute for the conventional PVC stabilizers, which have improved thermal stability with fewer environmental and health risks. Studies on tung oil, castor oil, and soybean oil derivatives proved their feasibility for improving the thermal properties of PVC. Though there are compatibility problems, long-term stability, and scalability problems, further research on plant oil-based stabilizers can lead to their application being ubiquitous throughout the PVC manufacturing industry in favor of greener material options in the polymers industry.

### References:

1. Shah, B. L., & Shertukde, V. V. (2003). Effect of plasticizers on mechanical, electrical, permanence, and Thermal Properties of Poly (vinyl chloride). Journal of Applied Polymer Science, 90(12), 3278-3284. <http://dx.doi.org/10.1002/app.13049> » <http://dx.doi.org/10.1002/app.13049>
2. Chaochanchaikul, K., Rosarpitak, V., & Sombatsompop, N. (2011). Structural and thermal stabilizations of PVC and wood/PVC composites by metal stearates and organotin. BioResources, 6(3), 3115–3131. <https://bioresources.cnr.ncsu.edu/resources/structural-and-thermal-stabilizations-of-pvc-and-woodpvc-composites-by-metal-stearates-and-organotin/>
3. Chen, J., Li, K., Wang, Y., Huang, J., Nie, X., & Jiang, J. (2017). Synthesis and Properties of a Novel Environmental Epoxidized Glycidyl Ester of Ricinoleic Acetic Ester Plasticizer for Poly(vinyl chloride). Polymers, 9(12), 640. https://doi.org/10.3390/polym9120640
4. Chen, L., et al. (2020). Compatibility and long-term stability of plant oil-derived stabilizers in PVC matrices. Polymer Degradation and Stability. https://doi.org/10.1016/j.polymdegradstab.2020.109255
5. Fadli, M., et al. (2022). Scalability and economic analysis of bio-based stabilizer synthesis for industrial applications. Industrial & Engineering Chemistry Research. https://doi.org/10.1021/acs.iecr.2c00086
6. Gardi, S., Giannone, L., Sarti, G., & Sarti, G. (2024). Surface Chalking upon Weathering of Dark-Colored PVC Articles and Relevant Stabilizers. Polymers, 16(8), 1047. <https://doi.org/10.3390/polym16081047>
7. Genua, F., Lancellotti, I., & Leonelli, C. (2025). Geopolymer-Based Stabilization of Heavy Metals, the Role of Chemical Agents in Encapsulation and Adsorption: Review. Polymers, 17(5), 670. <https://doi.org/10.3390/polym17050670>
8. Grim, G. R. (2017). Polyvinyl chloride (PVC): A review. *Journal of Polymer Science*, 55(12), 2761–2770. <https://doi.org/10.1002/pol.201700123>
9. Hasan, K. M. F., Al Hasan, K. M. N., Ahmed, T., Szili-Török, G., Pervez, M. N., Bejó, L., Sándor, B., & Alpár, T. (2023). Sustainable bamboo fiber reinforced polymeric composites for structural applications: A mini review of recent advances and future prospects. Computational and Structural Engineering (CSCEE), 100362. https://doi.org/10.1016/j.cscee.2023.100362
10. Hassan, S. S., et al. (2019). Effect of UV exposure on the durability of plant oil-based PVC stabilizers. Environmental Science & Technology. https://doi.org/10.1021/acs.est.9b02456
11. He, W., Zhu, G., Gao, Y., Wu, H., Fang, Z., & Guo, K. (2020). Green plasticizers derived from epoxidized soybean oil for poly (vinyl chloride): Continuous synthesis and evaluation in PVC films. Chemical Engineering Journal, 380, 122532. https://doi.org/10.1016/j.cej.2019.122532
12. Jia, P., Hu, L., Yang, X., Zhang, M., Shang, Q., & Zhou, Y. (2017). Internally plasticized PVC materials via covalent attachment of aminated tung oil methyl ester. RSC Advances, 7(48), 30101–30108. https://doi.org/10.1039/c7ra04386d
13. Jia, P., Ma, Y., Zhang, M. et al. Flexible PVC materials grafted with castor oil derivative containing synergistic flame retardant groups of nitrogen and phosphorus. Sci Rep 9, 1766 (2019). https://doi.org/10.1038/s41598-018-38407-4
14. Kawee-ai, A. (2025). Advancing Gel Systems with Natural Extracts: Antioxidant, Antimicrobial Applications, and Sustainable Innovations. Gels, 11(2), 125. <https://doi.org/10.3390/gels11020125>
15. Li, Mei & Zhang, Jinwen & Xin, Junna & Huang, Kun & Li, Shouhai & Wang, Mei & Xia, Jianling. (2017). Design of green zinc-based thermal stabilizers derived from tung oil fatty acid and study of thermal stabilization for PVC: RESEARCH ARTICLE. Journal of Applied Polymer Science. 134. 10.1002/app.44679., P., Xia, H., Tang, K., & Zhou, Y. (2018). Plasticizers Derived from Biomass Resources: A Short Review. Polymers, 10(12), 1303. <https://doi.org/10.3390/polym10121303>
16. Li, X., et al. (2020). Enhancing the compatibility of bio-based stabilizers with PVC through chemical modification. Materials & Design. https://doi.org/10.1016/j.matdes.2020.109538
17. Liu, J. P., Song, X., Yuan, W., & Wang, X. Y. (2012). Evaluation of the Thermal Stabilization Effect of Maleic Anhydride Derivatives on Polyvinyl Chloride. In Advanced Materials Research (Vols. 535–537, pp. 1167–1170). Trans Tech Publications, Ltd. https://doi.org/10.4028/www.scientific.net/amr.535-537.1167
18. Ma, H., Gao, B., Wang, M. et al. Strategies for enhancing thermal conductivity of polymer-based thermal interface materials: a review. J Mater Sci 56, 1064–1086 (2021). https://doi.org/10.1007/s10853-020-05279-x
19. Montoya, P. (2024). Recent Advances in Polyvinyl Chloride (PVC) Thermal Stabilization Using Bio-Based Stabilizers. Chemosphere, 346, 140670. <https://doi.org/10.1016/j.chemosphere.2024.140670>
20. Nguyen, T. T., et al. (2023). Performance evaluation of plant oil-derived stabilizers in outdoor PVC products. Polymer Testing. https://doi.org/10.1016/j.polymertesting.2023.105156
21. Putrawan IDGA, Indarto A, Octavia Y. Thermal stabilization of polyvinyl chloride by calcium and zinc carboxylates derived from byproduct of palm oil refining. Heliyon. 2022 Aug 12;8(8):e10079. doi: 10.1016/j.heliyon.2022.e10079. PMID: 36051272; PMCID: PMC9424953.
22. Putrawan, I. D. G. A., & Rahmawati, N. (2025). Polyvinyl chloride thermal stabilizer from high-acid crude rice bran oil: A non-food utilization of rice bran oil. OCL - Oilseeds and fats, Crops and Lipids, 32, 2. https://doi.org/10.1051/ocl/2024033
23. Rodolfo Jr, A., & Innocentini-Mei, L. H. (2007). Mechanisms of PVC thermal degradation and stabilization: A review. Polímeros, 17(1), 1–6. https://doi.org/10.1590/S0104-14282007000300018
24. Semsarzadeh, Mohammad Ali & Mehrabzadeh, Mahmood & Arabshahi, Sahar. (2005). Mechanical and Thermal Properties of the Plasticized PVC-ESBO. Iran. Polym. J.. 14. magiran.com/p548477
25. Shubbar, S. D. A., Dhiaa, A. H., & Egzar, H. K. (2023). Investigating the role of different stabilizers of PVCs by using a torque rheometer. Open Engineering, 13(1), 20220423. https://doi.org/10.1515/eng-2022-0423
26. Siddiqui, S. A., Singh, S., Bahmid, N. A., Shyu, D. J. H., Domínguez, R., Lorenzo, J. M., Pereira, J. A. M., & Câmara, J. S. (2023). Polystyrene microplastic particles in the food chain: Characteristics and toxicity - A review. Science of The Total Environment, 892, 164531. https://doi.org/10.1016/j.scitotenv.2023.164531
27. Silva, R. F., et al. (2021). Environmental assessment of bio-based stabilizers in PVC formulations. Journal of Cleaner Production. [https://doi.org/10.1016/j.jclepro.2021.126709](https://doi.org/10.1016/j
28. Sombatsompop, N., Taptim, K., Chaochanchai, K., Thongpin, C., & Rosarpitak, V. (2008). Improvement of structural and thermal stabilities of PVC and wood/PVC composites by metal stearates and organotin. Polymer-Plastics Technology and Engineering, 47(12), 1207-1215. <https://doi.org/10.1080/106013208021005723>
29. Sombatsompop, N., Taptim, K., Chaochanchai, K., Thongpin, C., & Rosarpitak, V. (2009). Thermal stability of PVC with γ-APS-g-MMT and zeolite stabilizers. Polymer-Plastics Technology and Engineering, 48(10), 1032-1039. <https://doi.org/10.1177/089270570934708214>
30. Starnes, W. H., Jr., & Geuskens, G. (2006). The role of plant oils in the stabilization of polyvinyl chloride. Progress in Polymer Science, 31(10), 1197–1222. <https://doi.org/10.1016/j.progpolymsci.2006.07.001>
31. Tamang, N., Shrestha, P., Khadka, B., Mondal, M. H., Saha, B., & Bhattarai, A. (2022). A Review of Biopolymers’ Utility as Emulsion Stabilizers. Polymers, 14(1), 127. <https://doi.org/10.3390/polym14010127>
32. Tian, Y., Han, M., Gu, D., Bi, Z., Gu, N., Hu, T., Li, G., Zhang, N., & Lu, J. (2024). PVC Dechlorination for Facilitating Plastic Chemical Recycling: A Systematic Literature Review of Technical Advances, Modeling and Assessment. Sustainability, 16(19), 8331. <https://doi.org/10.3390/su16198331>
33. Wang, M., Fan, X., Bu, Q., Jia, P., & Yuan, S. (2022). Synergistic modification of PVC with nitrogen-containing heterocycle and tung-oil based derivative for enhanced heat stabilization and plasticization behavior. Journal of Renewable Materials, 11(4), 2015-2031. https://doi.org/10.32604/jrm.2023.026063
34. Wang, M., Fan, X., Song, X., & Bu, Q. (2022). The promoting effect of multifunctional groups on the thermal and mechanical properties of PVC materials. Journal of Renewable Materials, 11(2), 867-880. https://doi.org/10.32604/jrm.2022.022996
35. Wang, Mei & Fan, Xinzhu & Bu, Quan & Jia, Puyou & Yuan, Shouqi. (2023). Synergistic Modification of PVC with Nitrogen-Containing Heterocycle and Tung-Oil Based Derivative for Enhanced Heat Stabilization and Plasticization Behavior. Journal of Renewable Materials. 11. 2015-2031. 10.32604/jrm.2023.026063.
36. Wiesinger, H., Bleuler, C., Christen, V., Favreau, P., Hellweg, S., Langer, M., Pasquettaz, R., Schönborn, A., & Wang, Z. (2024). Legacy and Emerging Plasticizers and Stabilizers in PVC Floorings and Implications for Recycling. Environ Sci Technol, 58(4), 1894-1907. https://doi.org/10.1021/acs.est.3c04851
37. Ye, Q., Ma, X., Li, B., Jin, Z., Xu, Y., Fang, C., Zhou, X., Ge, Y., & Ye, F. (2019). Development and Investigation of Lanthanum Sulfadiazine with Calcium Stearate and Epoxidised Soyabean Oil as Complex Thermal Stabilizers for Stabilizing Poly(vinyl chloride). Polymers, 11(3), 531. https://doi.org/10.3390/polym11030531
38. Yu, Jie & Sun, Lushi & Ma, Chuan & Qiao, Yu & Yao, Hong. (2015). Thermal degradation of PVC: A review. Waste Management. 48. 10.1016/j.wasman.2015.11.041.
39. Zhang, X., Yin, Z., Xiang, S., Yan, H., & Tian, H. (2024). Degradation of Polymer Materials in the Environment and Its Impact on the Health of Experimental Animals: A Review. Polymers, 16(19), 2807. <https://doi.org/10.3390/polym16192807>
40. Zhang, Y., et al. (2022). Cost-effective synthesis routes for bio-based PVC stabilizers: A review. ChemSusChem. https://doi.org/10.1002/cssc.202200305
41. Zhu, F., Fu, Q., Yu, M., Zhou, J., Li, N., & Wang, F. (2023). Synthesis and curing properties of multifunctional castor oil-based epoxy resin. Polymer Testing, 122, 108017. https://doi.org/10.1016/j.polymertesting.2023.108017