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Reduction of Formaldehyde Emission and Bonding Performance of Plywood Using Poplar Bark Extractive as a Bio-Based Scavenger

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Abstract

In the increasingly regulated environment where demand for natural and sustainable materials is high, this research explores the potential of forestry's by-product poplar-bark extractives as an environment-friendly, bio-based formaldehyde scavenger for plywood manufacturing. In the present study, bark extracts of poplar were collected, dried, and processed using an aqueous methanol extraction technique that was optimized for extreme extraction of poly phenolic constituents in poplar bark. The extract produced was subsequently incorporated into UF resins at different levels of concentration starting from 0.5 to 5% on the basis of resin weight. The different properties of adhesive and ply board like viscosity, gel time, bonding strength, and formaldehyde emission was carried. The experimental results highlighted the significance of the poplar bark extract for final product environmental performance and mechanical properties. Among the different formulations tested, the 5% concentration of bark extractives was determined to have given the best balance between the lower formaldehyde emission which was diminished by around 42% from that of the controlled UF adhesive and some achievable bonding performance with acceptable glue shear strength. Lower concentrations provided a moderate degree of reduced emission, while higher concentrations affected bond formation and efficiency.
In general, the research on poplar bark extractives finalized a promising eco-friendly and cost-effective alternative to reduce formaldehyde emissions in UF-bonded plywood .

1. INTRODUCTION

Composite wood-based materials such as plywood, particleboard, and medium-density fiberboard are widely used in construction, furniture production, and interior applications due to their cost-effectiveness and favorable mechanical properties. Urea–formaldehyde (UF) resins remain the most extensively used adhesives in these panels because of their low cost, rapid curing, strong bonding performance, and compatibility with high-speed industrial processing [2].

However, a major drawback of UF-bonded panels is the emission of formaldehyde, a volatile organic compound classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC) [1]. Formaldehyde emissions originate from residual free formaldehyde in resin formulations and from hydrolytic degradation of cured UF networks under humid or thermal conditions. Exposure to formaldehyde has been associated with respiratory irritation, allergic reactions, and long-term carcinogenic risks [1]. As a result, increasingly stringent emission regulations such as E0, E1, and F★★★★ standards have been implemented globally [2,7].

To mitigate formaldehyde emissions, several approaches have been investigated. One common strategy involves lowering the formaldehyde-to-urea (F/U) molar ratio during resin synthesis, although this often compromises adhesive performance [2]. Process optimization techniques, including control of pH and curing conditions, have also been explored [7]. Among these methods, the incorporation of formaldehyde scavengers into adhesive formulations has gained considerable attention as a practical and effective solution.

Conventional scavengers such as urea, ammonia-based compounds, and synthetic amines can chemically bind free formaldehyde, but they may introduce secondary environmental concerns or negatively affect bonding properties [7]. Consequently, there has been growing interest in renewable, bio-based scavengers derived from lignocellulosic biomass [2].

Natural materials rich in phenolic compounds—particularly tannins and lignins—have demonstrated strong reactivity toward formaldehyde due to the presence of phenolic hydroxyl groups capable of forming stable methylene bridges [8,9]. Several studies have reported successful reductions in formaldehyde emissions through the use of bark-derived additives. For example, birch bark incorporation into UF adhesives reduced emissions while maintaining acceptable bonding strength [3]. Larch bark extractives have been used effectively as formaldehyde scavengers in insulation panels [4], and beech bark has demonstrated similar functionality in plywood systems [5]. Additionally, plant-based fillers such as hemp flour have shown promising scavenging performance in melamine–urea–formaldehyde systems [6].

Bark, which constitutes approximately 10–20% of the total mass of harvested trees, is typically considered a low-value by-product of the forest industry [10]. Nevertheless, bark contains high concentrations of polyphenolic extractives, particularly condensed tannins, which are known for their strong chemical reactivity with aldehydes [8,9]. These compounds can immobilize formaldehyde through electrophilic substitution reactions, forming stable polymeric structures that reduce volatile emissions.

Among fast-growing species, poplar (Populus spp.) is widely cultivated for plywood and veneer production due to its favorable processing characteristics. Large quantities of poplar bark are generated annually as industrial residues. Despite its chemical richness, the potential of poplar bark extractives as formaldehyde scavengers in UF adhesive systems has not been sufficiently explored.

Therefore, the objective of this study is to evaluate the effectiveness of poplar bark extractives as bio-based formaldehyde scavengers in UF-bonded plywood. The study investigates their influence on adhesive rheology, curing behavior, formaldehyde emission, and bonding performance. By valorizing forestry residues and reducing reliance on synthetic additives, this research contributes to sustainable adhesive technology and circular economy principles in the wood composite industry.

2. MATERIALS AND METHODS

2.1 Materials

The bark of poplar trees(Populus) was collected and first cleaned by removing all the adhering dust particles, wooden fragments, and other impurities, afterward air-dried under laboratory conditions and allowed to equilibrate to a relatively stable moisture content of around 8%. The dry bark was then chopped in several batches by being fed into a laboratory-scale mill, aiming at producing an extremely fine powder. These crushed materials underwent sieving, and the particulates breaking through the mesh of 60 were carefully stored in airtight containers before further extraction to avoid moisture uptake.

As adhesives, the commercial urea-formaldehyde (UF) type resin thus chosen was a perfect match for the study. It had a solid content which was around 48%, the formaldehyde-to-urea (U/F) weight ratio was 1:2.4. These specifications are best used for producing interior-grade plyboards. The adhesives were stored at room temperature and peacefully mixed for being delivered to use.The plywood panels were made using eucalypatus veneers collected from different plant where they were used. Each veneer was 1.8 mm thick. The veneers carried a moisture content of about 6- 8% before any bonding was done.The bio-based poplar bark extractives were utilized to act as a formaldehyde scavenger during the manufacturing of Urea formaldehyde resin.

2.2 Bark Extraction

The poplar bark powder was subjected to the extraction of polyphenolic compounds using an aqueous methanol extraction technique capable of effectively recovering phenolic compounds without compromising their chemical activity.

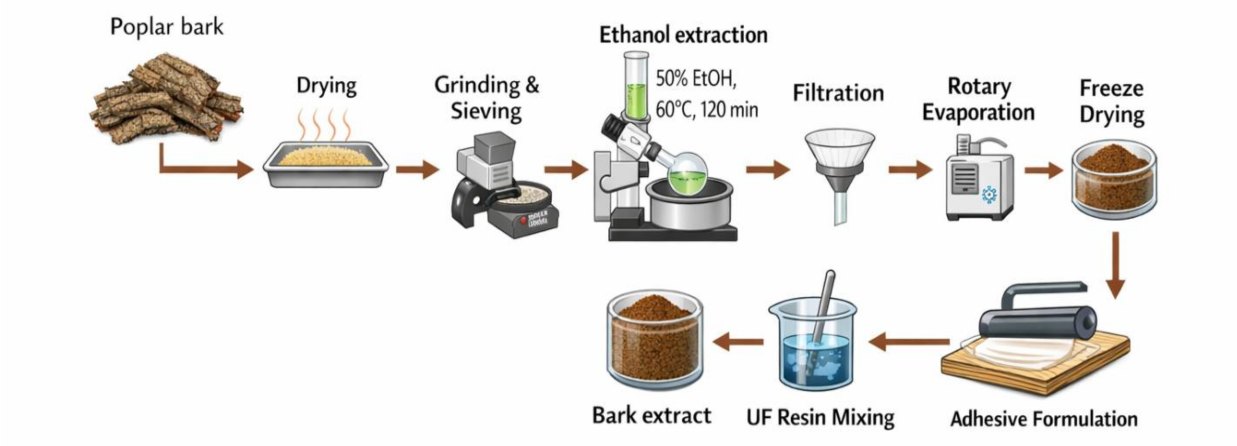

Figure 1. Flow chart of extraction of bio scavenger from popular bark

The use of a polar solvent comprising 30% (v/v) methanol and water in an extraction solvent mixture plays a major role in the dissolution of tannins and phenolic compounds in the tissue.

Extraction studies were performed at a liquid-to-solid ratio of 10:1 (ml solvent per gram of bark powder). This was done to assure complete mass transfer by readily preparing with enough solvent to dissolve the polyphenolic compounds and tannins from the bark tissues.

The mixture of bark and solvent was transferred into an extraction vessel that was temperature-controlled and then set at 60°C, with mechanical stirring, for a period of 5-6 hrs. Under moderate-temperature conditions, the release of phenolic extractives is favoured while ensuring that no very-labile compounds undergo significant thermal degradation. Afterwards, the extract was filtered off with filter paper to remove insoluble residue, hence leaving a clear solution of phenol-rich filtrate. The filtrate was concentrated by evaporation of solvent to undertake the removal of methanol from the solution. Low-temperature, vacuum solvent removal ensured preservation of the chemical integrity of the extracted compounds. The aqueous extract, thus concentrated, was made to a fine-crushed bark extract of powder form (crude), which could be weighed accurately, and appended to adhesive formulations. The dry extractive was stored at a low temperature in an airtight container for further usage.

The objective was to characterize the extracts and estimate their phenolic content. Total phenolic content was determined from the Folin–Ciocalteu method, which is an indicator of the redox properties of phenolic hydroxyl groups and is usually mentioned under GA. Also, the Stiasny precipitation method is applied to the condensed tannin content, which tells the percentage of responsive tannins capable of undergoing poly-condensation with formaldehyde.

2.3 Adhesive Preparation and Plywood Manufacturing

Adhesive formulas were designed through the incorporation of poplar bark extractives into the UF-resin at varying concentrations to assess their effectiveness as formaldehyde scavengers. Extractive concentrations of 0% (control),0.5%, 1%, 2%,3%, and 5% relative to UF-resin content were added during the resin manufacturing.

Figure 2. Plywood manufacturing by using bio scavenger in industrial scale

Because of its use as a filler or viscosity modifier in an adhesive formulation for the manufacture of plywood, wheat flour was added at 5% (based on resin solids) . The filler enhanced adhesive spread ability and the propensity to fill gaps between veneers. NH_4Cl content 0.1% of resin acted as a curing agent (hardener) for triggering the acid-catalyzed curing reaction of the UF resin during hot pressing. Following the addition of all ingredients, the adhesive mixture thoroughly mixed until homogeneous formulations were achieved.

Nineply,Ply wood panels were made from poplar as a workpiece in controlled laboratory conditions. These panels measured 400×400 mm and consisted of two face veneers and seven core veneer jointed in a crossed structure to manufactured 12mm plywood. The adhesive was applied to the surface of the veneers at a rate of 300-350 g/m² (DGL) the hand roller spreader to assure uniformity of the coating application process.

When adhesives were applied, the plywood patches were partially assembled prior to hot pressing. The hot pressing temperatures were 110-115 °C, the specific pressing pressure was 10.5 kg/cm2 and the pressing time was approximately 14 min. The same parameters as followed during the preparation of plywood bonded with UF resin were applied to cure the resin perfectly for bonding veneers in between. After the pressing interval, panels were removed from the press and then conditioned in an observational environment for subsequent testing and evaluation.

Table 1. Composition of UF adhesive formulations containing poplar bark extractive

Component	Parts by weight (Pbw)							
	Level of concentration (%)							
	UF 0	UF 1	UF 2	UF 3	UF 4	UF 5	UF 5	UF Resin
UF Resin (U:F Ratio)	1:2.4	1:2.4	1:2.4	1:2.4	1:2.4	1:2.4	1:2.4	100
Scavanger (%)	0	0.5	1.0	1.5	2.0	3.0	5.0	100
Wheat flour	10	10	10	10	10	10	10	100
NH4Cl	0.2	0.2	0.2	0.2	0.2	0.2	0.2	100

2.4 Plywood Panel Testing

(i) Effect of bio scavenger on Bonding and Mechanical properties

After pressing, all plywood panels were conditioned at 27 ± 2 °C temperature and 65 ± 5% relative humidity for 1 week until constant mass was achieved. After conditioning, plywood was cut into exact test samples according to the standard. Glue Shear strength of plywood panels were determined according to the standard IS 1734 :1983.

(ii) Effect of bio scavenger on Formaldehyde Emission from Plywood Panels

The free formaldehyde emission was measured using the desiccator method according to the standard JIS A 1460:2015and IS 13745. The test determines the quantity of formaldehyde emitted from plywood samples and absorbed in a specified volume of distilled water during 24 h in a glass desiccator. Ten test pieces from each type of plywood were prepared with dimensions of 150 ± 1 mm × 50 ± 1 mm (length × width) along with blank sample. They were then placed in a desiccator with an enclosed volume of 11 L with a glass-crystallizing dish containing 300 mL of distilled water. Samples were removed from the desiccators after 24 h and the obtained formaldehyde solution was prepared for spectroscopy and perforator method as described as per IS 13745.

Figure 3. Testing of formaldehyde content as per IS 13745

3. RESULTS AND DISCUSSION

3.1 Bark Extractive Characterization

This extraction process in raw bark material, suggesting a very good recovery of soluble components from the bark matrix in the extractive. Chemical analysis demonstrated the presence of rich levels of polyphenols. The total content of phenolic compounds in poplar bark extract stood at 285 mg gallic acid equivalent (GAE) per gram of extract, as brought about by the Folin–Ciocalteu method. This large phenolic concentration suggests good chemical reactivity and antioxidant potential-intuitively the specific characteristics required for active compounds of cell wall-scavenging materials. In addition, the percent of condensed tannins determined using the Stiasny precipitation method was 18.6, an indicator of a substantial amount of reactive tannin structures in the extract. Condensed tannins are considered important when it comes to formaldehyde scavenging because the flavonoid units harbor multiple reactive sites with the ability to generate stable methylene bridges with formaldehyde molecules. Indeed an abundance of phenolic hydroxyl groups and tannin-like structures invite the speculation that the materials may interact effectively with free formaldehyde from urea-formaldehyde adhesive systems. Thus, the findings suggest that poplar bark extractives could well act as natural formaldehyde scavengers that take up free formaldehyde through chemical bonding into the mentioned reactive phenolic sites, thereby lowering formaldehyde emissions from UF-bonded plywood panels.

3.2 Effect on Adhesive Properties

Due to the addition of poplar bark extractive in the UF adhesive system, the rheological and curing behavior of the adhesive formulations was distinctly influenced. When increasing the extractive content the flow time of the resin climbed stepwise from 18.5s in the control formulation to 26.0s with 5.0% extractive addition. This increased viscosity may be attributed to the existence of polyphenols and tannins of high molecular weight present in the raw material, which impart an additional range of intermolecular interactions within the adhesive matrix. Another factor that causes thicken adhesive systems could be due to the presence of hydrogen bonding and partial chemical interactions between the phenolic hydroxyl groups and UFresin molecules. The increased solid content, introduced initially by the extractive, might further increase internal friction of the adhesive mix and account for the jump in viscosity.

Table 2. Summary of adhesive properties, formaldehyde emission, and bonding performance

Extractive (%)	Flow time (sec.)/ B6	Gel Time (s)	Solid content (%)	Emission (mg/L)	Dry Strength (N/mm)
0	18	80	46.91	1.72	785
0.5	18.5	75	46.87	1.51	802
1	19.2	71	46.75	1.37	850
2	20.6	68	46.83	1.29	880
3	22.2	67	47.1	1.18	891
5	26.0	63	46.97	1.05	906

The curing behavior of the adhesive was also modified due to the bark extractives. The gel time decreased from 75 seconds to 65 seconds (appx 14%) at 5.0% extractives, indicating that the curing reaction had been accelerated. This reduction was observed in the gel time an indication was made that the bark extractive was helping the curing chemistry of the UF resin system.

The high acceleration of cure can be attributed to the phenolic hydroxyl groups in condensed tannins which are capable of reacting with free formaldehyde and methylol ($-CH_2OH$) groups formed in the reaction of UF resin condensation. These reactions result in additional crosslink formation in the adhesive system, giving rise to a high crosslinking density and a relatively short gelation time. Hence, bark extractive marketed as an active additive would provide the physical properties needed for adhesive polymerization and bonding.

In general, the above results indicated that poplar bark extractives affected the viscosity and curing performance of the adhesive in a concentration-dependent manner and should be considered while optimizing adhesive formulations for coating to ensure favourable bonds in plywood manufacturing.

3.3 Formaldehyde Emission Reduction

The presence of poplar bark extract, lowering the amount of formaldehyde in manufactured plywood produced by UF resin. The control plywood, lacking poplar bark extract, emitted 1.72 mg/L(JISA1460) and 19.16 mg/100gm (IS 13745)of formaldehyde. There was a statistically significant decrease when the bark extract, at any level, was present in the adhesive system, respectively leading to a drop in formaldehyde level with increasing bark extract content for different panels. Each combination of bark extraction with 1%, 3%, and 5% additions had emission values of 1.37 mg/L, 1.18 mg/L, and 1.05 mg/L.tasted as per JISA1460 and 17.68, 13.82 and 11.60 mg/100gm board tested as per IS 13745 It is obvious hereby that the formaldehyde level is decreased depending on the concentration of the poplar bark extract.Almost 40% reduction of formaldehyde emission was achieved by using 5.0% concentration of poplar bark extract.

In comparison, while one formulation with 5% extract exhibited about behaving a 40% decrease in formaldehyde emission, this value further reduced if the concentration of extract increases. It is important to note that all adjusted plywood panels met the requirement of F-★★★ emission standard by Japanese, which allows 1.50 mg/L. This finding suggests that an extractive of poplar bark can provide an efficient means of formaldehyde scavenging in UF-bonded plywood without requiring drastic changes of the manufacturing process.

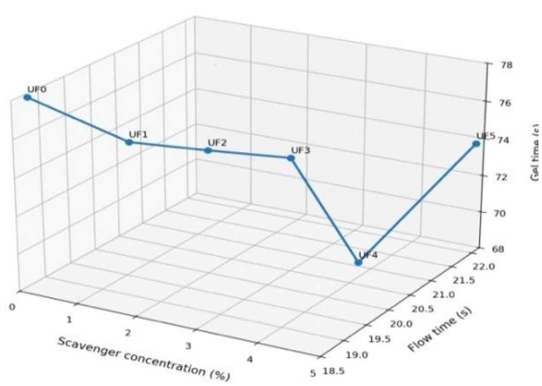

Figure 4. scavanger vs flow time vs geltime

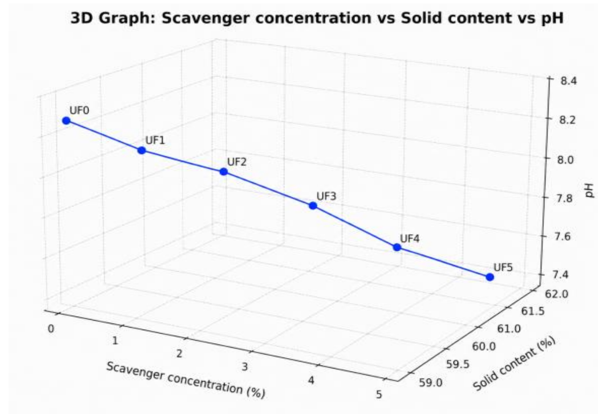

Figure 5. scavanger vs solid content vs P^H

The decrease in formaldehyde emissions could be elucidated by the chemical reactivity of polyphenolic compounds present in the bark extractives, in particular of condensed tannins. According to the fact framed well above, formaldehyde is an electrophilic molecule which favours nucleophilic aromatic sites in phenolic structures. The flavonoid A-rings on the tannins have reactive positions undergoing electrophilic substitution with respect to formaldehyde thereby forming methylene bridges between phenolic units. This reaction sets up a form of polymerized structure immobilizing free formaldehyde, trapping available volatile formaldehyde emission agents.

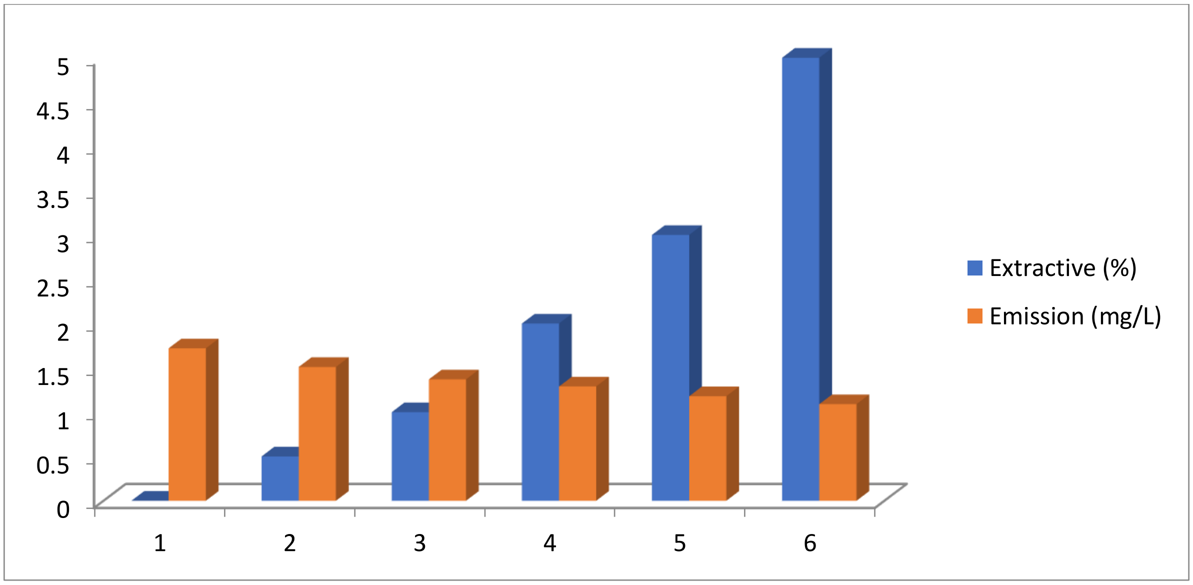

Figure 6. Scavenger conc(%) vs Formaldehyde emission(mg/L)

The figure shows formaldehyde emission values measured using the desiccator method for plywood panels prepared with 0%, 1%, 2%,,3% and 5% bark extractive addition. Emission decreases progressively from 1.72 mg/L in the control panel to 1.05 mg/L at 5% extractive addition. The dashed horizontal line indicates the Japanese F★★★ emission limit (1.50 mg/L). The results demonstrate concentration-dependent emission reduction due to formaldehyde scavenging by polyphenolic compounds.

Polyphenolic compounds can contribute to the formation of a network of crosslinks that adds some stability to the adhesive, and also the release of formaldehyde under long-term weathering or exposure to humid conditions.

3.4 Bonding Performance

The shear strength of the plywood boards was measured experimentally under both dry and wet conditions to investigate the influence of extractives from poplar bark upon bond quality. The shear strength measurements in the dry state were 785,802,850,880,891,906 N/mm for the plywood panels containing 0%, 0.5%,1%,3 %, and 5%, respectively. Thus, the bond strength reduces gradually as the percentage of extractive content increases. Noteworthy is that quality values drop close to the acceptable norms. All tested adhesive formulations gave a fairly good bonding strength when treated in accordance with IS 1734 (a minimum wet shear strength value of 800N/mm for interior-grade plywood), resulting in the acceptable bonding performance of modified adhesive systems.All the plywood samples including control made from 0%, 0.5%,1%,2%,3 %, and 5% is confirming water resistance taste as pass standard tested as per IS 848(2010) having wood failure more than 75%(requirement min.50%).

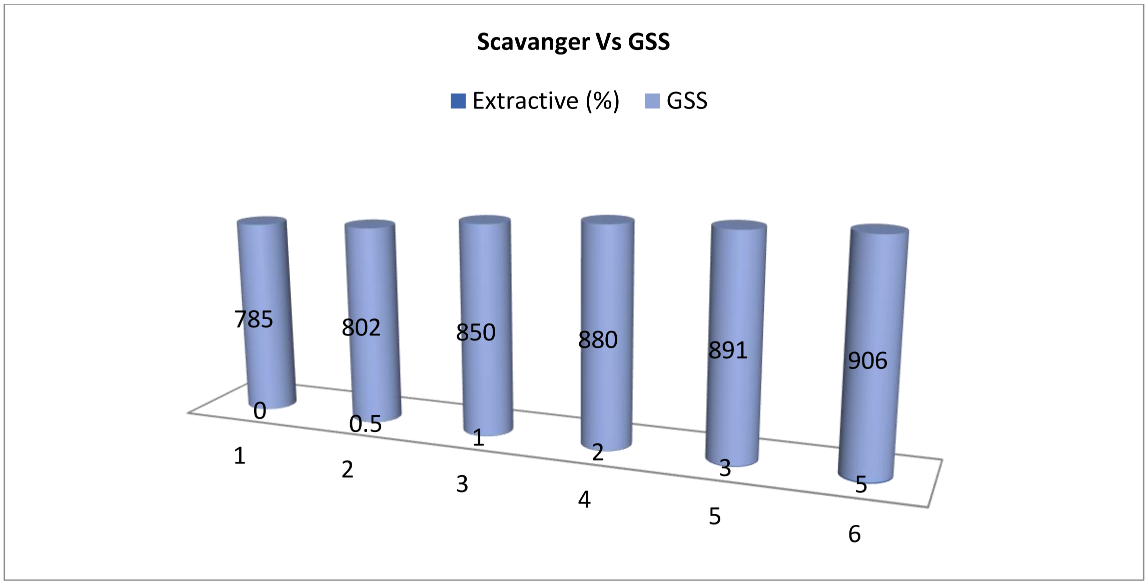

Figure 7. Bioscavanger vs Glueshear strength

The outcomes reported here indicate that the 5.0% class of bark extractive modifier stands as the best-suited dosage to deliver significant reduction in formaldehyde emission while still maintaining acceptable dry- and wet-bonding strength values for interior plywood applications. Such a result speaks to the potential application of poplar bark extractives as a practical and eco-conscious fill-in for UF-adhesive adhesion improvement without deterioration of structural performance requirements primarily.

4. CONCLUSIONS

This study has demonstrated that the extractives obtained from poplar barks can indeed act as credible bio-based formaldehyde scavengers for formaldehyde-laced urea-formaldehyde (UF)-bonded plywood systems. One set of results shows that the inclusion of bark extractives into UF formulations significantly cuts formaldehyde emissions and ensures the adhesion performances required. Specifically, the inclusion of 5.0% poplar extractive reduced the emissions of formaldehyde by about 42%, while both dry and wet shear strength values were high enough to satisfy the minimum specifications for an interior-grade plywood usage. These results evidence the feasibility of incorporating polyphenolic compounds of barks within conventional adhesive systems, retaining its structural integrity. One dark side of the reduction in formaldehyde emission takes place through chemical interaction of polyphenolics in bark extractives with free formaldehyde molecules already present in the adhesive system. Specifically, phenolic structures from the tannin react with formaldehyde to form more stable methylene bridges and to reduce the release back into the gas phase of formaldehyde molecules. This scavenging mechanism for lignocellulosic by-products suggests the potential of their further use as functional additives in synthetic resin systems.

The utilization of poplar bark extractives in adhesive formulations have several broader benefits. First, it is supportive of the valorisation of forestry by-products in transforming low-value residue bark into industrial materials with functional significance. Second, this developmental approach alleviates the dependence on synthetic formaldehyde scavengers and brings adhesive technology in line with sustainable material development. Third, it helps improve the quality of indoor bio-environment by reducing the emission of formaldehyde from wood-based panels. Therefore the properties contribute to the likelihood that bark-derived extractives will lead to a greener manufacturing process in the wood-composite sector.

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