Effect of Glutaraldehyde on the Antibacterial Resistance of Waste Office Paper-based Boards

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This research investigated the effect of glutaraldehyde solutions on antibacterial resistance of composite boards manufactured with different combinations of urea formaldehyde (UF) and glutaraldehyde (GA) binder adhesives. The composite boards were general-purpose furniture panels (*e.g.*, kitchen worktops, shelving, laboratory benchtops, or cabinet components) intended for household or workshop environments where surfaces may encounter microbial contamination from hands or spills, but not for direct food contact. Composite boards with varying UF/GA ratios and different binder solution concentrations were manufactured. The surfaces of these boards were treated with different numbers of layers (one or two) using GA solutions at 10% and 20% concentrations. The antibacterial performance of all samples was quantitatively evaluated by measuring the percentage of microbial growth. The results revealed a strong synergistic effect between the binder chemistry and surface treatment on antibacterial activity. The highest antibacterial performance was observed when the board containing 7.5% UF and 7.5% GA was treated with two layers of 10% GA solution, which suppressed microbial growth to a remarkably low level of 4.30%. Conversely, high-concentration GA applications adversely affected performance and noticeably reduced antibacterial efficacy in samples containing only pure UF or GA.

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INTRODUCTION

This study on paper-based composite boards and their bacterial resistance presents data from laboratory-based research on the bacterial resistance of paper-based composite boards following surface treatment with glutaraldehyde solutions in varying ratios and applied as single and double layers. The study also provides a brief overview of paper-based composite materials and evaluates wastepaper for the production of paper-based composite boards.

The antibacterial qualities of composite boards are crucial for two main reasons. First, according to the literature, bacterial contamination can cause the fibers themselves to deteriorate, eventually limiting the usability and physical integrity of composites (Gebeyehu *et al.* 2025). By functionalizing these composites, it is possible to ensure that they remain durable and useful for the duration of their intended use. Second, health concerns are more important than material integrity because microorganisms in the environment can rapidly propagate on untreated fibers, leading to skin infections or other health complications (Xu *et al.* 2021; Gebeyehu *et al.* 2025). These qualities are essential for both performance, health, and safety because without antibacterial functionality, the composite would not only deteriorate structurally but also directly endanger health of users.

Wood-based composite materials are widely used indoors for structural and decorative purposes, and they are commonly used to make furniture, flooring, ceilings, and walls (Alapieti *et al.* 2020). Wood-based composite boards are engineered wood products composed of natural wood fibers, wood chips, and synthetic additives. The main components are wood fibers or wood chips, wastepaper grades that form the core structure, and adhesives that bind these components together (Domínguez-Robles *et al.* 2020). Common binding agents used to improve the structural integrity and moisture resistance of boards include phenol-formaldehyde, urea-formaldehyde, and melamine-formaldehyde resins (Zhang 2023).

Recycling wood-based products, natural resource sustainability, and environmental impact reduction through waste evaluation are research topics that are gaining increasing economic value. Wood-based composite materials account for the majority of waste generated worldwide (Ojo *et al*. 2019). Paper-based products, which are wood-based composite materials, are produced in various types according to different criteria; they are consumed in large quantities around the world (Statista Research Department 2024).

Throughout the current paper-based board production process, several studies have examined the mechanical and physical properties of boards made from various wastepaper, including cement bags, office paper, newspaper, cardboard, decorative coating paper, and others (Krzysik *et al*. 1993; Hwang *et al*. 2005; Ayrilmis 2012; Ramezanian Sani and Enayati 2020; De Castro Sales *et al*. 2021; Moezzipour and Moezzipour 2021; Engin and Konukcu 2024; Konukcu and Engin 2024). Processing wastepaper is more cost-effective than processing products made of wood and chipboard (Grigoriou 2003; Nourbakhsh and Ashori 2010). However, a drawback of paper-based materials is that, due to their chemical composition and generally organic structure, they are vulnerable to bacterial growth and swelling when exposed to environmental moisture and humidity (Gamstedt 2016).

This study investigates the use of different mixtures of additives as binders in the board content to enhance their microbial resistance while simultaneously lessening the effects of more humid environmental conditions. For this purpose, the chemical substance used in the research and that will be modified is glutaraldehyde (GA). GA is used in hospitals as both a disinfectant and a medicine. It is known to be a biodegradable, biocompatible, and suitable crosslinking agent for polymeric materials (Goissis *et al*. 1999; Johnson *et al*. 1999). It has been shown that GA chemicals can interact with and bind to cellulosic and polysaccharide-based materials due to their cross-linking properties (Kildeeva *et al*. 2009; Jeon *et al*. 2019). Based on numerous studies in literature, GA was selected as a binder for the production of paper-based boards and as the primary ingredient in solutions for their surface treatments. In a study investigating the effects of solutions with different concentrations of GA applied as a surface treatment to paper material (Engin 2022), it was demonstrated that the coated paper had better mechanical and antibacterial resistance than untreated paper, depending on the concentration of the applied solution. In another study, GA-modified corn starch was used as a binder to reduce the use of formaldehyde-based glue in particleboard production, and the resistance of this application to biological attacks was investigated (Amini *et al*. 2018a). The results showed that particleboard using GA-modified starch as a binder was generally more resistant to fungal degradation. A study examining the water resistance of GA-modified commercial UF adhesive (Mamiński *et al*. 2006) found that samples containing GA exhibited improved cold water resistance. Furthermore, it was emphasized that adding GA to the UF adhesive did not negatively affect the resin's dry-state performance. Regarding the chemical interaction between urea-formaldehyde (UF) and GA, GA does not act as a simple additive or filler; rather, it chemically integrates into the UF molecular structure through a copolycondensation reaction. In essence, GA acts as a comonomer, replacing some formaldehyde molecules and covalently bonding to urea *via* its aldehyde ends. By adding GA to the UF matrix, more condensation processes are made possible, which raise the curing activation energy and create longer methylene chain structures (Dai *et al.* 2023). This change effectively increases the adhesive's water resistance by restricting the accessibility of hydrophilic sites within the cross-linked network (Mamiński *et al.* 2006). The intrinsic durability of the generated methylene and ether bridges suggests that these adhesives lack substantial biodegradability despite these performance gains, frequently requiring chemical or physical degradation mechanisms for disposal (Zhao *et al.* 2025). This integration of GA's flexible five-carbon chain ($-CH_2-CH_2-CH_2-CH_2-CH_2-$) into the rigid UF network controls the crosslinking density, reduces formaldehyde emissions (due to lower methylene-ether content) (Réh *et al*. 2021) dramatically improves the toughness and flexibility of the final thermoset resin (Dai *et al*. 2023). Akpenpuun and Gbadeyanka (2020) investigated particleboard production using urea-formaldehyde (UF), native cassava starch, and glutaraldehyde (GA)-modified cassava starch as binder adhesives. Their results showed that particleboards bonded with GA-modified starch had superior mechanical properties and reduced water absorption compared to those using unmodified cassava starch. Plywood boards produced with a NaOH-gelatinized GA-modified starch binder exhibited higher density and lower moisture content, which are advantageous for this type of composite (Amini *et al*. 2022). A review of relevant studies indicates that wood-based boards have been produced using various types of starch modified with GA as a binder (Amini *et al*. 2013; Amini *et al*. 2018b, 2019). These studies observed that starch modification with GA reduced the crystallinity index of the material, which in turn increased the strength of the produced wood composites. In another related study on boards using coconut fibers, GA-modified potato starch was used as an adhesive (Owodunni *et al*. 2020). In a study on plywood bonded with a UF-GA adhesive (Mamiński *et al*. 2008), the reinforcing effect of GA on the mechanical parameters of the adhesive was more clearly explained, particularly regarding wet strength.

This laboratory-scale study explored glutaraldehyde (GA) as a multifunctional agent in paper-based board production. It involved three novelties: using pure GA as a primary binder, blending GA with urea-formaldehyde (UF) resin as a hybrid binder system, and applying GA both internally and externally for antibacterial resistance. This approach marks the first comprehensive investigation of GA's role as both a binder and a surface treatment agent in this context.

EXPERIMENTAL

Materials

In the production process of waste office paper-based boards, shredded waste office paper was used as the primary raw material for the fiber-based structure. The binder system consisted of urea-formaldehyde (UF) resin modified with GA. The UF resin and Ammonium Sulfate ($(NH_4)_2SO_4$) hardener were provided by Yıldız Entegre Akhisar Facilities (Manisa, Türkiye). At 23.4 °C, the UF resin, with a solid content of 64.93%, had an F/U mole ratio of 1.15, a density of 1.28 g/cm^3, a pH of 7.91, and a viscosity of 84 cps.

Waste office paper was also collected from the main campus of Katip Celebi University in Izmir, Türkiye. The office papers, with an average grammage of 80 g/m^2 and a density of 0.75 g/cm^3, were classified and shredded for research. The shredded office paper was cut into 4 mm × 35 mm pieces using a paper shredder. The commercially available chemical glutaraldehyde branded “Alfasol,” and was supplied as a liquid with a 50% concentration. The technical characteristics of "Alfasol GA 50%" are listed in Table 1.

Table 1. Characteristic Properties of Glutaraldehyde

Molecular formula	$C_5H_8O_2$
Molecular weight	100.117 g / mol
Appearance	Colorless liquid form with intense odor
Density	1.06 g / cm^3
Melting point	-14 °C
Boiling point	187 °C

Tests Applied to Office Papers

The physical and structural properties of the wastepaper raw material used in the production of paper-based boards were determined according to relevant standard methods. Prior to the determination of paper characteristics, all test specimens were conditioned in accordance with the TAPPI T402 (2003) standard method. The TAPPI T410 (2013) standard method was used to determine the grammage of the office papers. The average thickness values of the papers were determined according to the TAPPI T411 (2010) standard method. Accordingly, a standard laboratory balance with a precision of 0.001 g was used for determining the grammage, and a caliper that measures thickness in microns was used. The densities of the office papers were then calculated by dividing their average grammage by their average thickness values, following the formula given in The ISO 534 (2011) standard method.

The TAPPI T412 (2011) standard method was used to determine the moisture content of the paper. In addition, the hydrophobic or hydrophilic character of the paper raw material was evaluated by determining the $Cobb_{60}$ value of the surfaces of the paper raw material according to the TAPPI T441 (2015) standard.

Even though the mineral filler content of the waste paper may vary by source, it was not characterised; nevertheless, most of these particles were retained during preparation, as no filtration step was employed in board production, and their existence and impact on the antibacterial resistance of boards were neglected and not analysed.

Preparation of the Solution for the Board Adhesive

The modified adhesive, named GUF, was applied to a composite board blend made from waste office paper. This adhesive is produced by modifying the chemical GA, a five-carbon dialdehyde known as a high-level disinfectant, with UF adhesive and Ammonium Sulfate ($(NH_4)_2SO_4$) hardener.

To compare and demonstrate the synergistic effect of the GUF adhesive, only UF and GA chemicals were also applied as adhesives. Glutaraldehyde solution was diluted to two concentrations (10% and 20%) when preparing the GUF and GA adhesives, as shown in Table 2. To ensure a homogeneous solution of the adhesive components, the modification process was carried out using a heated magnetic stirrer. Because GA is a polymerizable chemical whose polymerization rate increases with the concentration of hydroxyl ions (Margel and Rembaum 1980), alkaline pH values (8 to 13) were used when preparing the solution.

Table 2. GA Concentrations and GUF Adhesive Ratios Used in Board Production

GA Concentration	GUF Adhesive Ratios (%) by Board Weight		Specimen Groups
	UF	GA	
0%	10	0	A10-0
	15	0	A15-0
10%	0	10	B0-10
	5	5	B5-5
	0	15	B0-15
	7.5	7.5	B7.5-7.5
20%	0	10	C0-10
	5	5	C5-5
	0	15	C0-15
	7.5	7.5	C7.5-7.5

Board Manufacturing

The waste office paper, classified and designated for use in board production, was shredded and cut into strips of equal size, 4 mm x 35 mm, using a paper shredder machine (Everest JP-716C) as a preliminary step. The prepared shredded paper was then mixed with prepared adhesive solutions (modified GUF and unmodified GA and UF) in a laboratory-type 80 L mechanically operated mixer with a rotor speed of 30 rpm using a compressor-powered spray technique to achieve the most homogeneous mixture possible.

Appropriate amounts of paper and chemicals were weighed according to the GUF content and mixing ratios specified in Table 2. All weighing operations for paper preparation were performed based on oven-dry weight calculations, considering the paper's moisture content. Additionally, 10% of the weight of the adhesive used in the board blend, 21% solid content Ammonium Sulfate ($(NH_4)_2SO_4$), was added as a hardener.

The prepared board blend was placed into pre-press molds, a cube-shaped mold made of fiberboard with four closed sides, custom-made in a carpentry workshop, with a surface area of 320 x 360 mm to form pre-board prototypes. These prototypes were pressed in a laboratory-type hydraulic hot press (CEMILUSTA SSP-180 T Model, Istanbul, Türkiye) for 5 min at a temperature of 170 °C and a pressure of 3 MPa. This process produced paper-based boards with a thickness of 10 mm and a density of approximately 650 kg/m^3. After hot pressing, the boards with the specified density and thickness were conditioned at 20 °C and 42% humidity for 2 weeks and cut to size according to test standards.

Application of Antibacterial Surface Solution

The mixture of antibacterial solutions was prepared with distilled water, commercial Alfasol Glutaraldehyde chemical (GA 50%), and carboxymethyl cellulose (CMC 2%). After heating the CMC (2%) solution and distilled water to 50 °C, the mixture was continuously stirred until the CMC was completely dissolved. Antibacterial solutions containing 10% and 20% GA, along with 2% binder CMC, were homogenized before application. These antibacterial coating solutions were applied evenly to both surfaces of each board sample using a paintbrush. A total of 4 mL of the solution were dropped onto the surface of each 5 cm x 5 cm board specimen using a pipette. To ensure uniform distribution, the dropped solution was then spread evenly over the entire surface of the board using a new brush at a constant speed and pressure. As shown in Table 3, the surfaces of the produced boards (coded B0-10, B5-5, A10-0, B0-15, B7.5-7.5, A15-0, C0-10, C5-5, C0-15, and C7.5-7.5) were treated with solutions containing GA at concentrations of 10% and 20%, applied in either one or two coats. The first coats were applied, and the board specimens were allowed to dry naturally for 24 h under normal room conditions, then the second coats were applied using the same process. The antibacterial properties of 50 different board groups, including those with and without surface treatment, were thus investigated.

Table 3. Surface Treatment Codes (by Layer Count & GA Content)

Surface Coating Code	GA (%)	Binder (CMC) (%)	Number of Coating Layer
C1	10	2	1
C2	20	2	1
C3	10	2	2
C4	20	2	2

Figure 1 provides an outline of the entire experimental process. This procedure included raw material and adhesive preparation, board manufacturing, preparation and application of an antibacterial surface solution to the board surfaces, and assessment of the antibacterial properties of the boards in relation to their adhesive content and surface treatments.

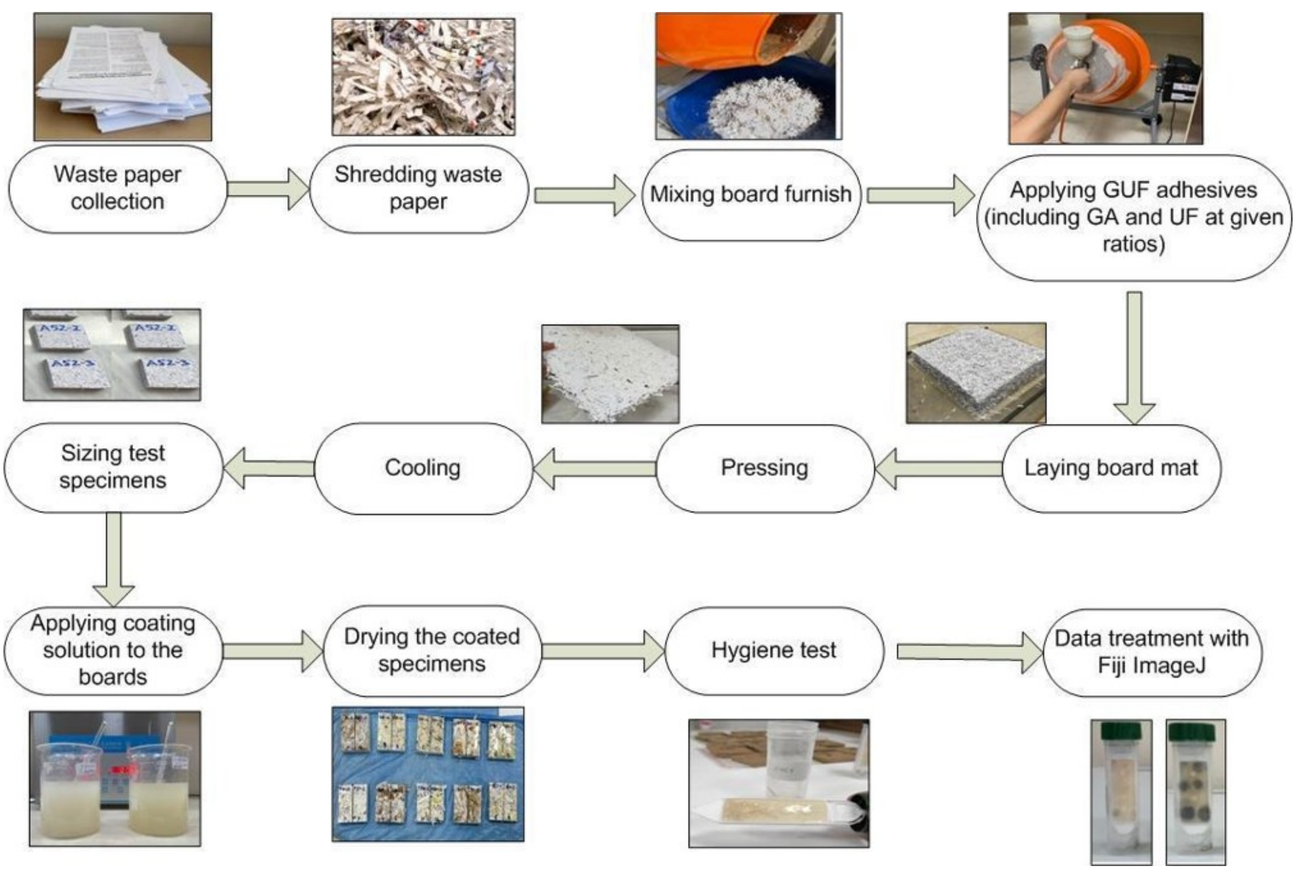

Fig. 1. Schematic depiction of experimental design

Determination of the Mechanical Properties of the Boards

The manufactured boards were cut to the required sample size and tested to determine their mechanical properties in accordance with European Standards (EN). Mechanical tests were conducted on an IMAL IB600 universal testing machine. EN 310 (1994) standard was used to determine the bending strength (MOR) and the modulus of elasticity (MOE), whereas EN 319 (1999) standard was used to measure the tensile strength perpendicular to the surface (internal bond (IB)) of the boards. Five replicates were evaluated for each of these properties.

Determination of the Antibacterial Resistance of the Boards

In this preliminary study, the resistance to surface microbial colonization of the coated composite boards was evaluated using microbial samples collected from the surfaces of unwashed laboratory workbenches and human hands. It is important to note that this method does not follow standardized antibacterial testing protocols and therefore provides semi-quantitative, sample-dependent results intended only as an initial assessment, not as a definitive measure of antibacterial efficacy. The Hytech Slide® hygiene test kit was used to observe microbial growth on the surfaces of the composite boards. To monitor microbial proliferation, all test samples were placed in an oven at 35 °C for 120 h after being in contact with the growth medium in the test kits for 5 to 6 s.

To quantitatively assess bacterial and mold growth, the culture media from the kits were analyzed using Fiji/ImageJ software. The extent of surface colonization was determined by calculating colony density, expressed as the percentage of the total surface area of the culture medium occupied by microbial growth —a metric that reflects visible coverage rather than reduction in viable bacterial counts. Colony density was determined by processing representative images with ImageJ-Fiji and Excel software, as shown in Fig. 2. Owing to the lack of a standardized protocol, the results presented herein should be interpreted as preliminary and are not directly comparable with those obtained from established antibacterial testing methods.

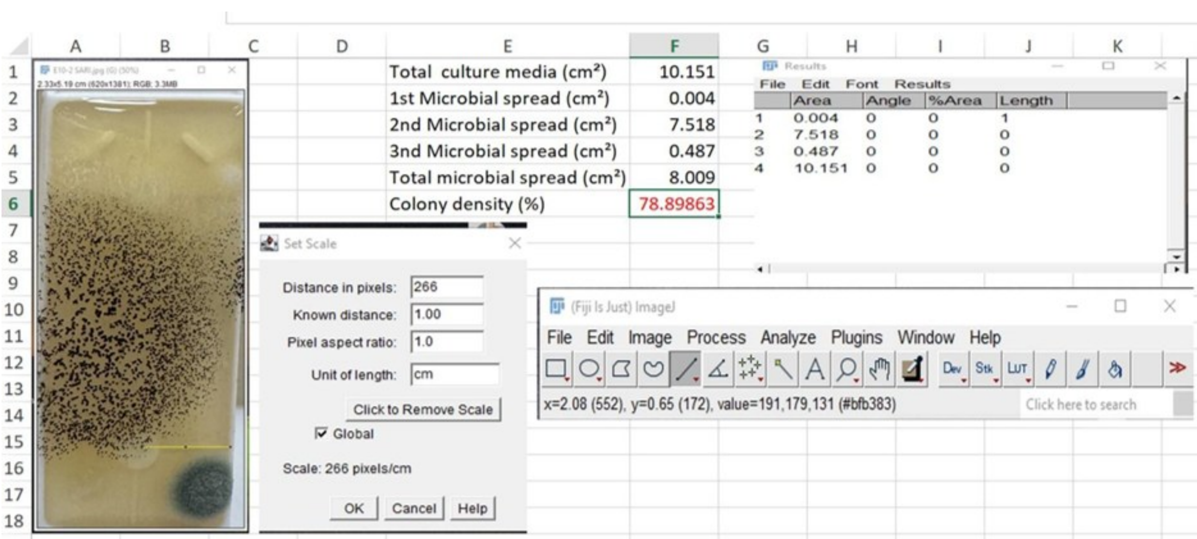

Fig. 2. Representative images for quantitative analysis of colony density

RESULTS AND DISCUSSION

The physical and structural properties of the wastepaper used in composite board production were characterized. Table 4 summarizes the physical characteristics of the wastepaper feedstock. The paper had a grammage of 80 g/m² and a thickness of 110 µm, corresponding to a calculated density of approximately 0.675 kg/m³. This relatively low density suggests a porous, lightweight fibrous structure. Additionally, a moisture content of 5.2% and a $Cobb_{60}$ value of 33 g/m² indicate moderate water absorbency.

Table 4. Characteristic Properties of Waste Office Paper Used in Board Manufacturing

Grammage (g/m^2)	Thickness (µm)	Density (kg/m^3)	Moisture Content (%)	$Cobb_{60}$ (g/m^2)
80	110	0.675	5.2	33

Table 5 presents the mechanical properties (MOR, MOE, and IB) of the boards. In general, the mechanical performance of the specimens was significantly influenced by the production parameters and component ratios. The highest mechanical performance was obtained from the A15-0 board specimen, which contained a higher concentration of UF resin alone (16.86 MPa for MOR, 2464.14 MPa for MOE, and 0.132 MPa for IB). It was found that mechanical property was largely determined by the component combination ratios when Groups B (including 10% GA concentration) and C (including 20% GA concentration) were evaluated within themselves. In both groups, B5-5 and C5-5 specimens, which contain 5% UF and 5% GA, demonstrated a distinct superiority compared to other specimens in each group. On the other hand, specimens containing only GA, such as B0-15 (3.75 MPa for MOR and 423.97 MPa for MOE) and C0-10 (3.88 MPa for MOR and 441.42 MPa for MOE), showed a significant decrease in mechanical stability (about a 60% loss for MOR and about a 70% loss for MOE). This result can be explained by the 5:5 mixture ratio (5% UF and 5% GA) producing a homogeneous distribution and the best possible synergistic impact within the material.

Table 5. Mean Values of Mechanical Properties of the Boards

Sample Codes	MOR (MPa)	MOE (MPa)	IB (MPa)
A10-0	11.38 (0.14)	1818.01 (0.08)	0,072
A15-0	16.86 (0.15)	2464.14 (0.12)	0,132
B0-10	4.29 (0.39)	621.44 (0.21)	Not applicable
B5-5	9.05 (0.22)	1507.83 (0.25)	Not applicable
B7.5-7.5	6.04 (0.07)	657.42 (0.24)	0,034
B0-15	3.75 (0.11)	423.97 (0.12)	Not applicable
C0-10	3.88 (0.12)	441.42 (0.16)	Not applicable
C5-5	9.27 (0.26)	1518.37 (0.27)	0,042
C7.5-7.5	8.37 (0.17)	828.09 (0.11)	Not applicable
C0-15	4.14 (0.27)	432.60 (0.19)	Not applicable

Values in parentheses are coefficient of variations.

When the internal bond (IB) strengths of the specimens were examined, consistent measurements could not be obtained for many specimens—with the exception of the specimens containing UF—and the values were recorded as “Not applicable.” This indicates that the formulations in question have inadequate fiber-matrix interfacial bonding, which leads to an internal structural deficit.

Total viable bacteria on the hygiene kit surfaces were quantified using culture-based methods. Colony density, expressed as the percentage of surface area covered by microbial growth, was calculated, and the results are shown in Fig. 3.

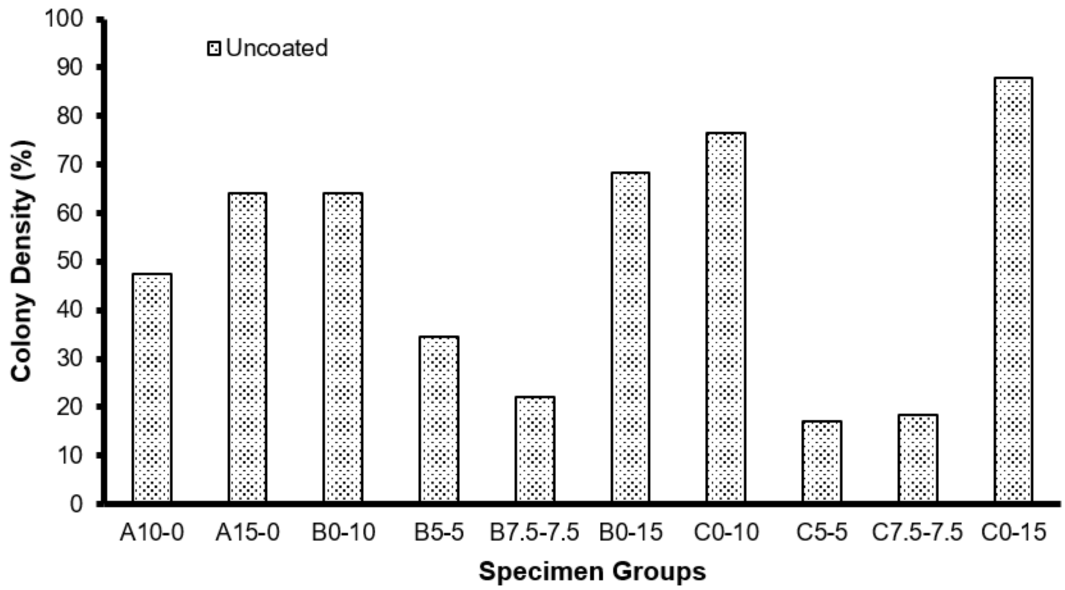

Fig. 3. Antibacterial performance of composite boards as a function of adhesive content

As shown in Fig. 3, the boards with the most pronounced antibacterial properties—groups C5-5, C7.5-7.5, B7.5-7.5, and B5-5—were those manufactured using a combination of UF and GA binders. This outcome indicates a potential synergistic effect on antibacterial activity when both binders are used together. Boards manufactured with GA adhesive alone (groups B0-10, B0-15, C0-10, and C0-15) exhibited very low antibacterial activity. The increased microbial growth observed on specimens with higher GA concentrations (C0-10 and C0-15) suggests that the adhesive may have served as an additional nutrient source, thereby enhancing bacterial proliferation. The A15-0 board specimen, which contained a higher concentration of UF resin alone, exhibited inferior antibacterial properties compared to the A10-0 board specimen, which had lower UF content. This suggests that, contrary to expectations, excessive UF concentration may diminish antibacterial efficacy. Increasing the UF concentration in the board formulation enhanced antibacterial activity, as evidenced by the improved performance of board groups B5-5 *versus* C5-5 and B7.5-7.5 *versus* C7.5-7.5. In contrast, for boards containing GA as the sole adhesive, increasing the GA concentration diminished antibacterial properties, as shown by the reduced efficacy of groups C0-10 and C0-15 compared to groups B0-10 and B0-15, respectively. This suggests that GA exhibits noticeable antibacterial activity only when UF is present, indicating a synergistic effect. The board C5-5, which contains 5% UF and 5% GA (prepared from a 20% adhesive solution), showed superior antibacterial properties compared to all other formulations.

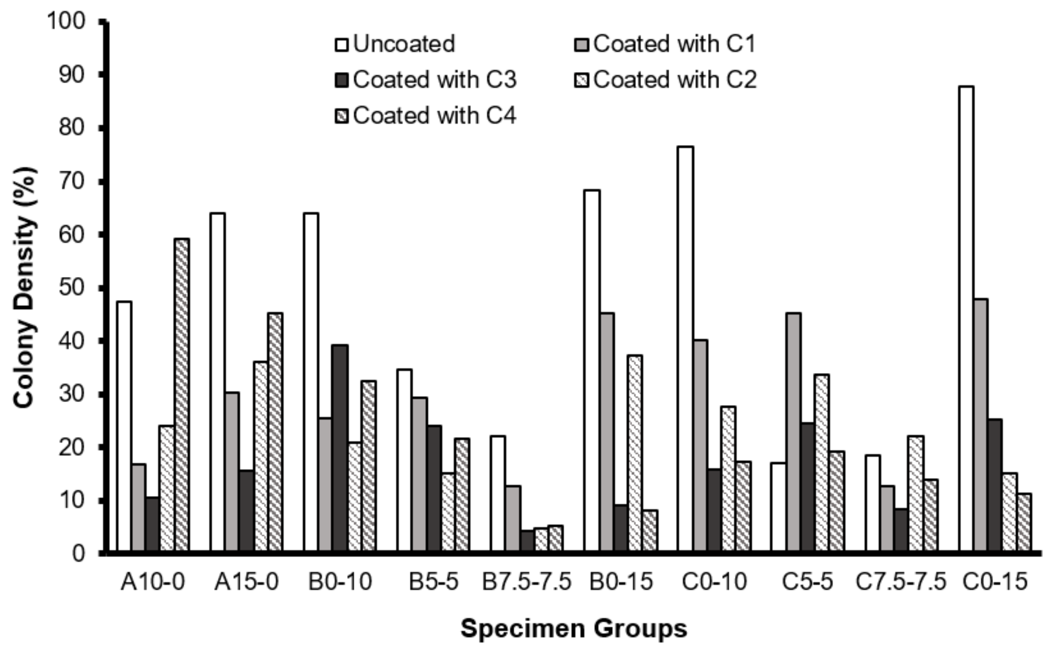

Fig. 4. The effect of glutaraldehyde surface treatment on the composite groups

In Fig. 4, colony densities in culture media were measured to evaluate the effects of GA concentration in the surface coating solution and the number of applied coating layers on the antibacterial resistance properties of the composite groups. The coating solutions, prepared with a constant binder concentration (2% CMC), were applied to the surface using two distinct parametric variations. To assess the effect of increasing GA concentration in a single-layer application, samples C1 (10% GA, 1 layer) and C2 (20% GA, 1 layer) were prepared. At the same time, samples C3 (10% GA, 2 layers) and C4 (20% GA, 2 layers) were designed to investigate the synergistic effect of combining multi-layer application with increased concentration. The data in Figs. 3 and 4 indicate that surface coating performance was determined not only by the concentration of the primary component (GA) or the number of applied layers but also by its proportional relationship with the other adhesive component (UF). Specifically, under fixed GA concentrations of 10% and 20%, which make up the binder content of the composites, a gradual increase in the concentration of UF from 0% to 15% induced substantial variations in critical coating parameters. These include the adhesion of the coating solution to the composite board surface, its homogeneity, and the resultant barrier properties. As shown in Fig. 4, the surface coating treatments greatly enhanced the antibacterial properties of all composite board groups except for the C5-5 group. In particular, the C0-15 composite board group showed the greatest reduction in colony count and the most remarkable improvement in antibacterial properties after surface coating treatment compared to its control group.

The boards with the strongest antibacterial properties—the control specimens of groups B5-5, B7.5-7.5, C5-5, and C7.5-7.5—were produced using a combination of UF and GA binders, as previously shown in Fig. 3. This trend improved with surface treatment, especially in the B5-5 and B7.5-7.5 groups, which further enhanced their superior antibacterial performance compared to the other board groups after the surface coating was applied. However, the results did not identify a single coating formulation that provided optimal antibacterial efficacy for the surface of every type of composite board.

In summary, the findings of this study support that a high level of antibacterial performance can be achieved through the strategic incorporation of GA into both the binder formulation and the surface coating. As earlier cited literature suggests, using GA-modified starch as a binder for board production, the resistance of boards to biological attacks (Amini *et al.* 2018a), mechanical properties, and reduced water absorption were improved (Akpenpuun and Gbadeyanka 2020). This is consistent with prior reports documenting the successful application of GA modification across various biomass types—including starch and coconut fiber (Amini *et al.* 2013; Owodunni *et al.* 2020). The current data of this work contribute to this understanding by showing that GA significantly increases the antibacterial resistance of paper-based boards when applied as a surface treatment and used as a pure binder or especially mixed with UF resin.

CONCLUSIONS

1. This study has presented a preliminary, semi-quantitative investigation into optimizing microbial surface colonization resistance in composite boards using different mixtures of urea formaldehyde (UF) and glutaraldehyde (GA) binders, and a GA-based surface coating. Results indicate that antibacterial efficacy is affected by binder type, concentration, surface coating composition, and the number of coating layers applied.
2. Applying two layers of a 10% GA surface treatment (coating C3) to samples B7.5-7.5 significantly minimized microbial growth, showcasing the highest antibacterial performance. This reflects a synergistic effect between the optimal binder formulation and surface treatment.
3. In contrast, the antibacterial properties of samples containing a single binder type varied after surface treatment, with certain formulations showing a reduction in antibacterial performance. This observation highlights the complexity of the interactions between binder composition and surface treatment.
4. Optimizing both the binder system and the final surface treatment strategy is essential for achieving high antibacterial activity. This study demonstrates that paper-based boards can be modified to reduce visible surface microbial colonization, it is important to emphasize that the method used does not follow standardized antibacterial testing protocols. The results are semi-quantitative, sample-dependent, and intended as an initial screening rather than a definitive measure of antibacterial efficacy.

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