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# Formaldehyde Emission in Micron-Sized Wollastonite-Treated Plywood Bonded with Soy Flour and Urea-Formaldehyde Resin

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**Abstract:** Soy flour was partly substituted for urea-formaldehyde (UF) resin with different content to investigate its effect on formaldehyde emission in three-layer plywood panels. In each square meter of panels, 300 g of resin was used (wet weight basis of resin). Micron-sized wollastonite was added to the resin mixture at 5% and 10% consumption levels (wet weight basis of resin) to determine its potential effects as a reinforcing filler to mitigate the negative effects of addition of soy flour. Results showed a decreasing trend in formaldehyde emission as soy flour content increased to 20%. The highest shear-strength values were observed in panels with 10% and 15% soy flour content. The addition of wollastonite did not have a significant effect on formaldehyde emission, but it decreased the shear strength in soy-treated panels, although the values were still higher than those of control panels. Wollastonite significantly mitigated the negative effects of soy flour on the water absorption and thickness swelling of panels. It was concluded that 10% of soy flour and 5% of wollastonite provided the lowest formaldehyde emission and the most optimum physical and mechanical properties.

**Keywords:** biobased resins; formaldehyde emission; minerals; wollastonite; wood composite panels

## 1. Introduction

Adhesives play an important role in the efficient utilization of wood resources and in the development and growth of the forest product industry. Adhesive bonding of solid wood and wood particles of various sizes is a key factor for the production of modern, functional wood products, used in a variety of applications. For centuries, wood was bonded using biobased adhesives until synthetic adhesives, mainly thermosetting ones, gradually took over in the 20th century, as they were typically regarded as more effective, cost-efficient [1], and stable for use in humid conditions. Today, the main classes of thermosetting adhesives are amino-based, phenolic, and isocyanate resins. The utilization of these thermosetting adhesives is considered more economical, and reactive adhesives with quick curing behavior are versatile in a range of properties in the cured state. These adhesives have dominated the wood composite industry for many decades. Within this group, urea-formaldehyde (UF) resins are the most important adhesives in terms of quantity. Due to their low-cost raw materials, their rapid curing, their high dry-bond strength, and a colorless glue line, UF-based adhesives are almost exclusively used for producing wood-based materials, such as particleboard or medium-density fiberboards for interior applications [2]. When products are utilized in conditions exhibiting higher humidity, UF resins are usually modified with significantly more expensive compounds such as melamine, phenol, or resorcinol [2]. It has to be mentioned that the final adhesive composition in use depends on the requirements of the wood-based material such as the required strength properties, the expected moisture resistance, the production cost of the finished product, and the desired formaldehyde emission class.

When it comes to formaldehyde emission from wood-based composites, it has to be mentioned that emission can originate from (i) synthetic-free formaldehyde that is not polymerized into the network, which emits during or quickly after panel production, (ii) formaldehyde released due to adhesive hydrolysis, which emits over the lifetime of the panel depending on moisture and temperature, and (iii) biogenic sources [2]. The discussion surrounding formaldehyde started as early as the mid-1960s, as reviewed by Roffael et al. [3], and various stages of reduced emissions were achieved in the 1970s and intensified in the 1980s when the carcinogenicity of formaldehyde in rats and mice after long-term inhalation exposure was reported. The topic of formaldehyde in indoor environments was intensively and controversially discussed by various authors, as reviewed by Salthammer et al. [4]. Driven by the standard requirements specified by the local authorities in, e.g., Europe, Japan, and the United States of America (USA), formaldehyde content and emissions from wood-based composites have been continuously reduced over the last few decades.

During the last few decades, the wood industry made great effort with many innovations in amino resin technology to gradually reduce formaldehyde emissions in order to fulfill the individual product and standard requirements for each type of composite. These can be summarized as follows: (i) low-formaldehyde-content resins, (ii) formaldehyde scavenger additives, (iii) post treatments, and (iv) alternative adhesives [1].

For the first type of approach, the first tendency has been to prepare engineered UF resins of progressively lower molar ratio, at levels much lower than 1:1 [5], which has become rather common in industry today. This is due to the attempt to minimize formaldehyde emissions from wood panels bonded with UF resins. One of the drawbacks of the much lower than 1:1 molar ratio has been identified in an increase in the tendency of the UF resin to form increasingly present crystalline domains upon hardening as a result of hydrogen between linear molecules [6–8]. At higher molar ratios, the hardened resin is amorphous, affording better adhesion and better bonding performance. The overly high crystallinity drawback was very recently solved [9] by blocking the formation of hydrogen bonds using transition metal ion–bentonite nanoclay through in situ intercalation and, thus, converting the crystalline domains of the UF resins to amorphous polymers. Addition of 5% nanoclay to the UF yielded in excess of 50% better adhesion and almost 50% lower formaldehyde emission, thus resulting in a marked improvement in performance with a low level of crystallinity. In the same trend, the potential introduction of a very acidic pH condensation step in the preparation of UF resins, inducing the formation of occasionally considerable amounts of uron (a cyclic intramolecular urea methylene ether) in the UF resins with lower formaldehyde emission, has attracted some research interest [10,11]. This initial work indicated that introduction of such an acid step can lead to UF resins with improved bonding strength, but also higher post-cure formaldehyde emission.

With regard to the second approach, formaldehyde scavengers, capable of capturing formaldehyde either physically or chemically and forming stable products, are added to UF resins or to wood particles before pressing [12,13]. These additives should provide long-term formaldehyde emission reduction, in principle, along the panel's life. Examples used in industry include the addition of urea in an aqueous solution or powder form, organic amines, scavenger resins, sulfites, functionalized paraffin waxes, and porous absorbers such as pozzolan and charcoal [14]. Very good formaldehyde emission reduction is obtainable by adding sodium metabisulfite to the resin, by adding tannin solution to urea-formaldehyde resin, or by using different starch derivatives [15,16].

The third approach involves treatments that are applied after pressing. Currently used methods include panel impregnation with formaldehyde-scavenging species, such as aqueous solutions of ammonia, ammonium salts, or urea. Another option is the creation of diffusional barriers in the panel surfaces that keep formaldehyde confined, by using paints, varnishes, veneers, laminates, or resin-impregnated papers [17,18].

Alternative adhesives involve isocyanate-based adhesives and biobased wood adhesives. The concern about formaldehyde emission vapor levels from UF adhesives has brought isocyanate adhesives to the fore, where formaldehyde emission does not occur as no formaldehyde is added. pMDI (polymeric methylenediphenyl isocyanate) is an excellent adhesive and can be used in markedly smaller proportions than formaldehyde-based adhesives to bind wood composites. Another attractive option is biobased adhesives. The term biobased adhesive has come to be used in a very well specified and narrow sense to only include those materials of natural, nonmineral origin which can be used as such or after small modifications to reproduce the behavior and performance of synthetic resins. Thus, only a limited number of materials can be currently included, at a stretch, in the narrowest sense of this definition. These are tannins, lignin, carbohydrates, unsaturated oils, proteins and protein hydrolysates, dissolved wood, and wood welding by self-adhesion. An excellent review on this topic was recently published by Pizzi et al. [1]

The most common biobased adhesives are protein-based sourced from animal bones and hides, milk (casein), blood, fish skins, and soybeans. Soy protein is obtained from soybean and has been used for centuries as a wood adhesive. In the context of wood composite production, soy protein was added to phenol formaldehyde resin to lower formaldehyde emission, but lower water resistance is an important limitation [19]. Formaldehyde-free wood composites were obtained using an adhesive based on soy flour and glyoxal, a nontoxic, but less reactive, aldehyde [20]. It was reported that the use of soy protein combined with polyamidoamine-epichlorohydrin (PAE) resins yields a strong and water-resistant product that is commercially available for wood composites [21]. Another interesting formaldehyde-free adhesive system, successfully tested in the production of plywood and OSB (Oriented Strand Board) panels, is based on a combination of soy flour, polyethylenimine, maleic anhydride, and sodium hydroxide [19]. Hosseini et al. [22] reported that the partial replacement of urea-formaldehyde adhesive with soy flour, particularly with a substitution rate of 15%, significantly reduced the formaldehyde emission, while it did not significantly influence the shear strength, under both dry and wet conditions. Kawalerczyk et al. [23] applied five types of flours (rye, hemp, coconut, rice, and pumpkin) as fillers with urea-formaldehyde resin in plywood manufacture. It was reported that the type of flour had a major influence on the properties of resin mixture such as gel time, solid content, and viscosity. The use of hemp flour as a filler led to a substantial decrease in free formaldehyde content.

Under this context, the present study was carried out to primarily investigate the effects of partial substitution of soy flour for UF resin and the consequent effects on formaldehyde emission and on some key physical and mechanical properties. In order to minimize possible negative effects on properties due to the use of soy flour, an innovative approach was made in an extra set of boards, to add micron-sized wollastonite. Micron-sized wollastonite is a mineral that was successful in improving the physical and mechanical properties in medium-density fiberboards and particleboards [24–28]. It significantly improved the shear strength of polyvinylacetate resin [29]. It was even effective in improving the fire properties in wood-based composite panels and solid wood [29–35]. Therefore, this study continued with the addition of micron-sized wollastonite to the resin mixture to determine its potential effect on the properties of plywood panels produced with a mixture of UF resin and soy flour.

## 2. Materials and Methods

### 2.1. Panel Production

Three-layer plywood panels were produced, using poplar veneer (*Populus deltoides*) with 2.1 mm of thickness. The dimensions of the produced panels were 350 × 350 mm. The target thickness of the panels was 6 mm. For each square meter of panels, 300 g of urea-formaldehyde resin was used (wet weight basis of resin). Glued veneers were hot-pressed for 5 min at 130 °C. The specific pressure of plates was 1.5 MPa, and the total nominal pressure of the plates was 20 MPa. Once produced, 25 mm of each side was trimmed to avoid inconsistent edges (Figure 1). Except for the formaldehyde emission tests, all produced panels were kept in a conditioning chamber (25 ± 3 °C, relative humidity 60–65%) for a week before test specimens were cut to size. The specimens were kept under the same conditions for two more weeks before tests were carried out. The target density of the panels was 0.55 g·m$^{-3}$.


**Figure 1.** Panels produced and trimmed, ready to be cut to size for each test according to the relevant standard (**A**); front surface of a trimmed plywood panel (**B**).

## 2.2. Resin Application

UF resin was purchased from Amol Resin Company (Amol, Iran). The viscosity of the resin was 200–400 cP, with 47 s of gel time, and a density of 1.277 g/cm$^3$. Defatted soy flour (SF) was purchased from Behpak Company (Behshahr, Iran). SF contained 47% (*w*/*w*) protein (Ghahri et al. 2016). SF was substituted for UF resin at 5%, 10%, 15%, and 20% (*w*/*w* dry weight). SF and UF were mixed for 10 min using a magnetic stirrer. Micron-sized wollastonite was prepared by Mehrabadi Machinery Mfg Co. (Tehran, Iran) (Table 1). Wollastonite was mixed with the resin for 10 min at 5% and 10% (*w*/*w* dry weight basis of resin). Once the resin was prepared, it was applied onto the veneers in less than 1 min. Just before applying the prepared resin on veneers, 1% ammonium chloride was mixed as a hardener (dry weight basis of UF resin). Within 4 min of the application of resin on veneers, the layers were arranged and then hot-pressed.

**Table 1.** Chemical composition of the wollastonite ingredients on weight basis. (Data from Hassani et al. [35].

| Component | Proportion (% *w*/*w*) |
|---|---|
| $SiO_2$ | 46.96 |
| CaO | 39.77 |
| $Al_2O_3$ | 3.95 |
| $Fe_2O_3$ | 2.79 |
| $TiO_2$ | 0.22 |
| $K_2O$ | 0.04 |
| MgO | 1.39 |
| $Na_2O$ | 0.16 |
| $SO_3$ | 0.05 |
| Water | 4.67 |

### 2.3. Measurement of Formaldehyde Emission

Formaldehyde emission (FE) in the present study was measured on the basis of European standard specifications (EN 717-3/Part 3) [36]. From each of the five replicate panels, three specimens were cut for the formaldehyde emission test. Necessary coordination was made so that specimens were tested immediately to minimize sources of error. The dimensions of the FE test specimens were 25 × 25 × 6 mm. Flask type 2 (with a volume of 500 mL) was employed. FE tests were carried out at the temperature of 40 ± 2 °C, for a duration of 180 min. In this test method, FE specimens were hung in vertical position at 40 mm above the distilled water (50 mL) at the bottom of the flask (Figure 2). The flask was then cooled (using a mixture of ice water) for 30 min to ensure absorption of the emitted formaldehyde in the distilled water inside the flask. Acetylacetone spectrophotometric analysis was used to determine the amount of formaldehyde in each flask. The determination of formaldehyde emission was based on the Hantzsch reaction. In this method, aqueous formaldehyde reacted with ammonium ions and acetylacetone to yield diacetyldihydrolutidine (DDL). DDL has a maximum absorption capacity at wavelength of 412 nm. A T60 visible range spectrophotometer was used in the present study, with a fixed 2 nm spectral bandwidth. The absorption amount was then expressed as mg of formaldehyde/kg of dry wood.

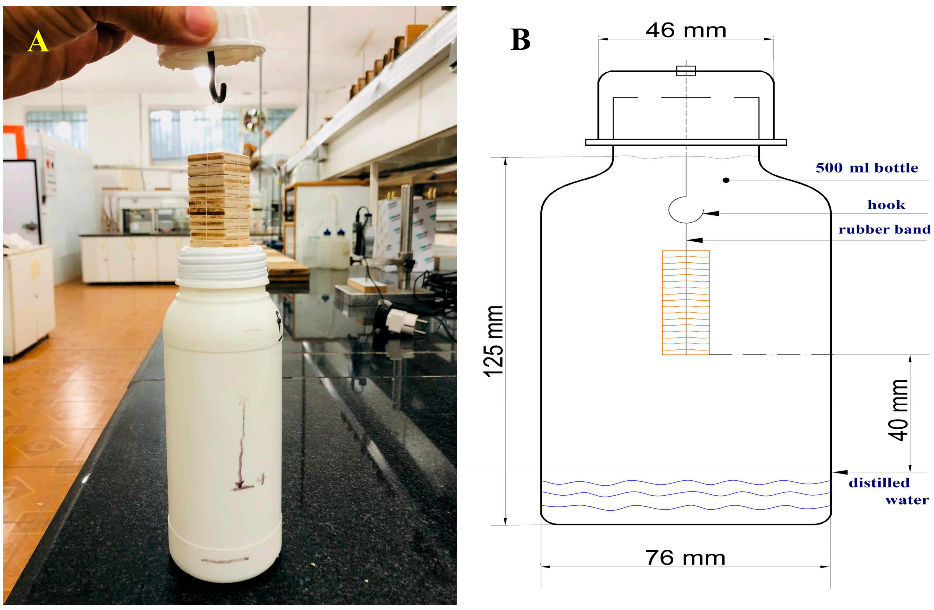


**Figure 2.** Test apparatus for measurement of formaldehyde gases, type 2 for the flask method (1:500 mL bottle with a top made of polyethylene plastic; 2: hook to hang specimens; 3: rubber band to suspend specimens within the flask; 4: distilled water at the bottom of the flask): (**A**) the actual flask with a set of specimens; (**B**) linear drawing of the flask.

### 2.4. Shear-Strength Test

Specimens for the shear-strength test were prepared according to European standard specifications EN 314-1: 2004 (Figure 3). Specimens were tested using a universal test machine model STM-20, produced by Santam Engineering Design Co. (Semnan, Iran). Loading speed was 1 mm/min. Shear strength was calculated using Equation (1).

$$S\,S = \frac{F_{\max}}{A}\ (\text{MPa}), \tag{1}$$

where $F_{\max}$ is the maximum failing force, and $A$ is the shear area in the specimen.

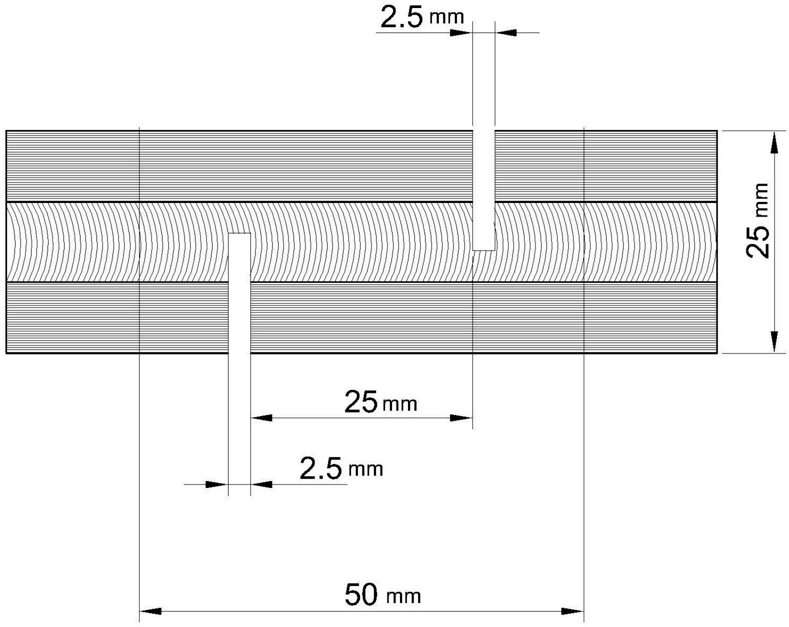


**Figure 3.** Linear diagram of shear-strength test specimen according to European standard specifications EN 314-1: 2004.

### 2.5. Delamination Test

Delamination properties of the produced plywood were determined on the basis of voluntary standard specifications for plywood, provided by "The Hardwood Plywood and Veneer Associations (ANSI/HPVA HP-1, 2004). On the basis of the specifications, three specimens (50.8 mm × 127 mm) were cut from each panel. They passed three rounds of soaking/drying cycles. Each cycle comprised 4 h of soaking in water at 24 ± 2 °C, and then a drying period of 19 h with heating at 50 ± 1 °C. According to the specifications, a panel is acceptable for interior use if <5% of specimens delaminate after the first soaking/drying cycle. For exterior applications, delamination should not occur in >15% of the specimens. By definition, delamination is any continuous opening between two layers of plywood that is longer than 5.08 cm (or 2 in), deeper than 0.64 cm (or 0.25 in), and wider than 0.008 cm (or 0.003 in).

### 2.6. Statistical Analysis

One-way analysis of variance (ANOVA) was carried out in a completely randomized design and experiment with SAS software, version 9.2 (2010) at a 95% level of confidence. Duncan's multiple-range test was then performed to discern similar groupings among treatments for each property. Hierarchical cluster analysis was then performed using SPSS/18 (2010). Clusters included dendrograms by means of Ward's methods using squared Euclidean distance intervals.

## 3. Results and Discussion

### 3.1. Preliminary Study

In a preliminary study, 5%, 10%, 15%, and 20% UF resin was replaced with soy flour to gain a better estimation of the most effective combination to decrease formaldehyde emission. Results of the preliminary study demonstrated a clear decreasing trend in formaldehyde emission (FE) as soy flour content increased (Figure 4). This is in line with the data reported in the literature. Hosseini et al. [22] reported that the partial replacement of urea-formaldehyde adhesive with soy flour, particularly with a substitution rate of 15%, significantly reduced the formaldehyde emission. A similar observation was also made by Kawalerczyk et al. [23] who applied five types of flours (rye, hemp, coconut, rice, and pumpkin) as fillers with urea-formaldehyde resin in plywood manufacture. All soy-treated panels showed a significant decrease in formaldehyde emission in comparison to control panels. The highest and lowest formaldehyde emissions were observed in the control panels (130.1 mg/kg) and panels with 20% soy flour (88.6 mg/kg), respectively. No significant difference was observed between formaldehyde emissions in panels produced with 10%, 15%, and 20% soy flour, although the FE trend was a decreasing one as soy flour content increased to 20%. Two factors potentially contributed to this behavior. The first one may have been the great dependence of formaldehyde emission on the resin content. A lower content of formaldehyde in the adhesive mixture causes a lower level of formaldehyde emission from the panel. In fact, a higher substitution of UF resin with soy flour results in a lower formaldehyde emission. Another factor is the reaction of free formaldehyde with amino groups present in the soy flour. Pereira et al. [37] found that the use of soy protein as a natural formaldehyde scavenger in wood particleboard production can contribute to a decrease in the formaldehyde content of particleboard panels, without significantly affecting the properties of the panels

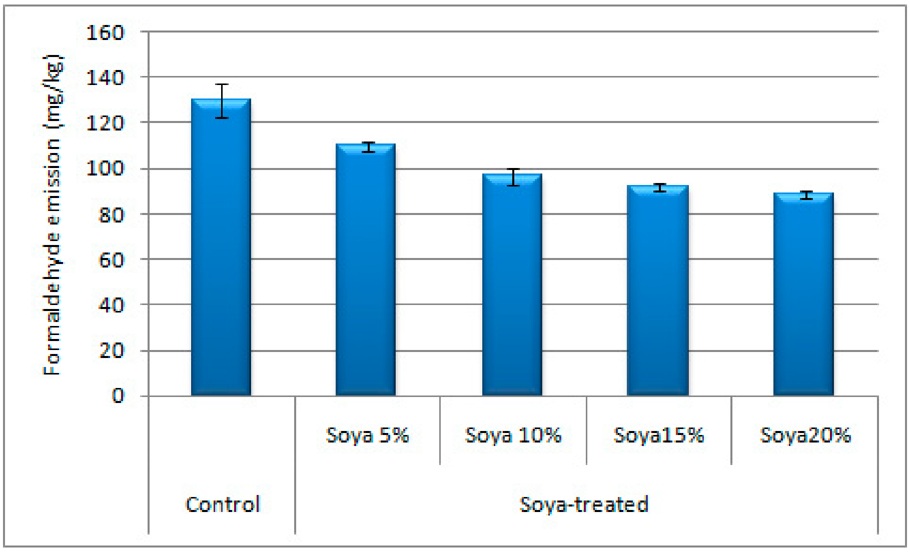


**Figure 4.** Formaldehyde emission (mg/kg) in three-layer plywood panels produced with urea-formaldehyde resin and 5%, 10%, 15%, and 20% soy flour substitution of UF resin.

The shear strength of all panels produced in the preliminary phase of the study was also measured to find out the effects of the addition of soy flour on at least one mechanical property. Results showed that the shear strength values of all treatments were more than the standard limit of 1 MPa, even the control panels (1.55 MPa). The highest shear strength was observed in panels with 15% soy flour content (2.1 MPa); that is, soy flour resulted in a 34% increase in shear strength. The soy flour content of 5% did not have a significant effect on the shear strength of plywood panels (Figure 5). A further increase in soy flour content to 20% resulted in a decrease in shear strength (1.8 MPa), although it was still higher than that of the control specimens. Results of the delamination tests showed that all panels successfully passed the test (Table 2). This indicated that substitution of soy flour for UF resin (for soy flour contents lower than 20%) cannot significantly affect the delamination property of plywood panels. This finding is in accordance with a previously reported study, in which it was found that the partial replacement of UF adhesive with soy flour, particularly at substitution rates of 10% and 15%, did not significantly affect the shear strength of plywood under both dry and wet conditions [22].

Cluster analysis using the two properties of formaldehyde emissions and shear-strength values in the preliminary phase demonstrated similar clustering of the control panel with panels containing 5% soy flour (Figure 6). This indicated that 5% soy flour is too low to significantly influence the studied properties of plywood panels. The other three panels were distinctly clustered away from control panels. In order to benefit from the maximum shear strength, as well as a satisfactory decrease in formaldehyde emission, the optimal soy flour contents of 10% and 15% were chosen for the next phase in which wollastonite was added to the UF resin along with soy flour.

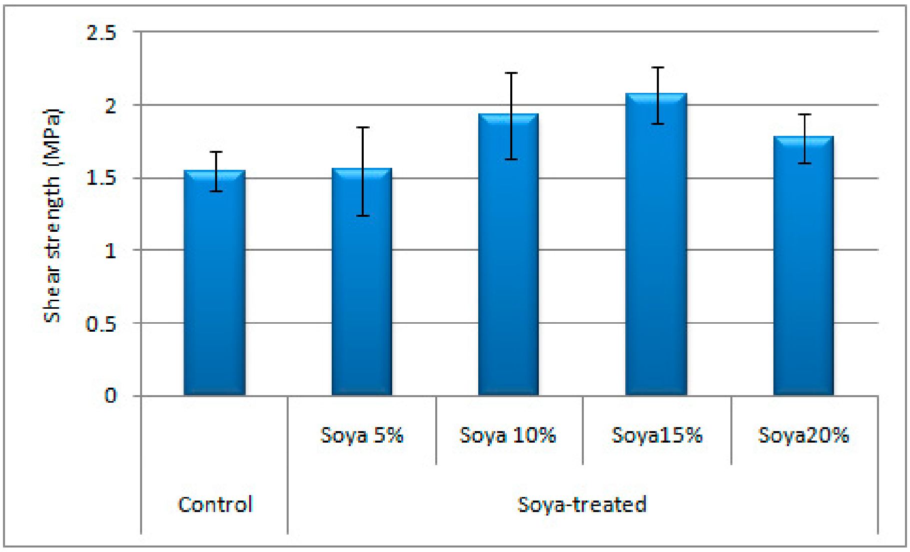


**Figure 5.** Shear strength (MPa) in three-layer plywood panels produced with urea-formaldehyde resin and 5%, 10%, 15%, and 20% soy flour substitution of UF resin.

**Table 2.** Delamination test on plywood produced with different binders.

| Binder | First Round [1] | Third Round [2] | Result [3] |
|---|---|---|---|
| UF [4] 100% | 1/20 | 1/20 | P |
| UF 95% + SF [5] 5% | 0/20 | 0/20 | P |
| UF 90% + SF 10% | 1/20 | 1/20 | P |
| UF 85% + SF 15% | 0/20 | 0/20 | P |
| UF 80% + SF 20% | 0/20 | 0/20 | P |

[1] No. of delaminated cases after the first round of the soaking/drying cycle. [2] No. of delaminated cases after the third round of the soaking/drying cycle. [3] P = testing passed, F = testing failed. [4] Urea-formaldehyde resin content. [5] Soy flour content.

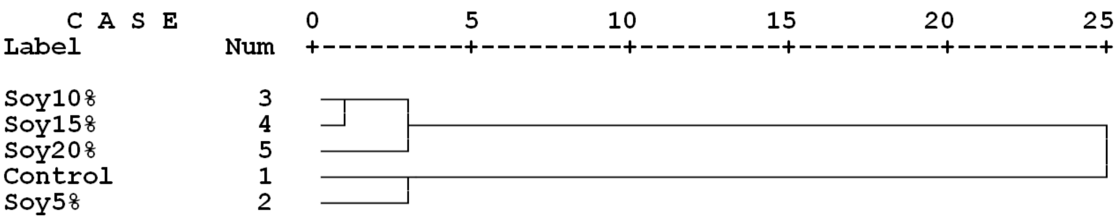


**Figure 6.** Cluster analysis of five different three-layer plywood panels produced with urea-formaldehyde resin, and 5%, 10%, 15%, and 20% soy flour substitution for UF resin (Soy% = soy flour content).

### *3.2. Main Phase of the Study*

In the second phase of the study, 5% and 10% wollastonite gel (W) was added to panels made with a mixture of UF resin and soy flour (only two optimal SF contents of 10% and 15% were tested in the main phase). Results illustrated that, apart from slight fluctuations which were attributed to the standard deviation among different specimens, the addition of wollastonite had no significant effect on formaldehyde emissions (Figure 7). However, both contents of wollastonite had a decreasing impact on shear strength (Figure 8), although the shear strength in W-added panels was still higher than that of control panels. The decrease in shear strength was attributed to the absorption of part of the resin by wollastonite particles. Results of the delamination tests revealed that all panels passed this test, indicating that the addition of SF or wollastonite did not have a significant impact on the delamination of plywood panels (Table 3).

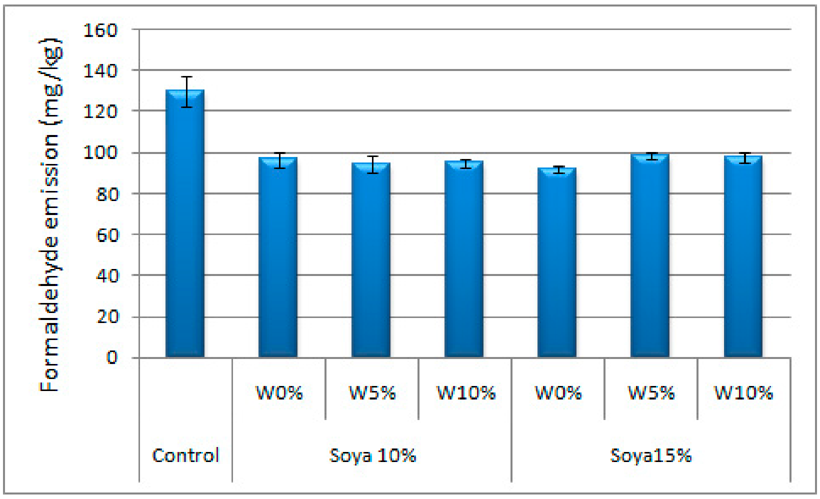


**Figure 7.** Formaldehyde emission (mg/kg) in three-layer plywood panels (Soy% = soy flour content; W% = wollastonite content).

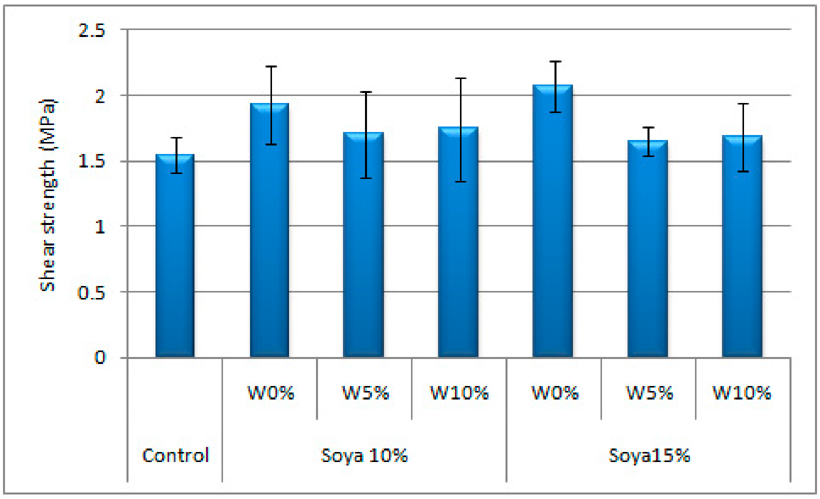


**Figure 8.** Shear strength (MPa) in three-layer plywood panels (Soy% = soy flour content; W% = wollastonite content).

Substitution of soy flour for UF resin at both levels of 10% and 15% significantly increased the water absorption (WA) and thickness swelling (TS) (Figures 9A and 10A after 2, 24 and 720 h and Figures 9B and 10B at various time intervals). The increases were significant at 2 h, 24 h, and the long-term immersion of 720 h. The increase was attributed to the water hydrophilicity of soy flour [38–41]. Addition of wollastonite (both W contents of 5% and 10%) to the resin mixture resulted in a significant decrease in water absorption, almost reaching the same value as in the control panels. This decrease was attributed to the reinforcing effect of wollastonite in the resin mixture. Similar reinforcing effects were previously reported to improve the shear strength of polyvinyl acetate resin [31] and the fire-retarding property of acrylic–latex paint [42]. With respect to thickness swelling, 5% wollastonite significantly decreased the TS to nearly the same level as in the control panels. However, TS values of panels containing 10% W were still nearly as high as the values of soy-treated panels. That is, a W content of 10% could not mitigate the negative effect of soy flour on thickness swelling. It was concluded that 10% wollastonite was too high, thereby absorbing UF resin rather than acting as reinforcing filler to improve thickness swelling; therefore, a W content of 5% is recommended as an optimum.

**Table 3.** Delamination test on plywood produced with different binders and with the addition of wollastonite.

| Binder | First Round [1] | Third Round [2] | Result [3] |
| --- | --- | --- | --- |
| UF [4] 100% | 1/20 | 1/20 | P |
| UF 90% + SF [5] 10% | 1/20 | 1/20 | P |
| UF 90% + SF 10% + W [6] 5% | 1/20 | 2/20 | P |
| UF 90% + SF 10% + W 10% | 0/20 | 0/20 | P |
| UF 85% + SF 15% | 0/20 | 0/20 | P |
| UF 85% + SF 15% + W 5% | 0/20 | 0/20 | P |
| UF 85% + SF 15% + W 10% | 0/20 | 0/20 | P |

[1] No. of delaminated cases after the first round of the soaking/drying cycle. [2] No. of delaminated cases after the third round of the soaking/drying cycle. [3] P = testing passed, F = testing failed. [4] Urea-formaldehyde resin content. [5] Soy flour content. [6] Wollastonite content.

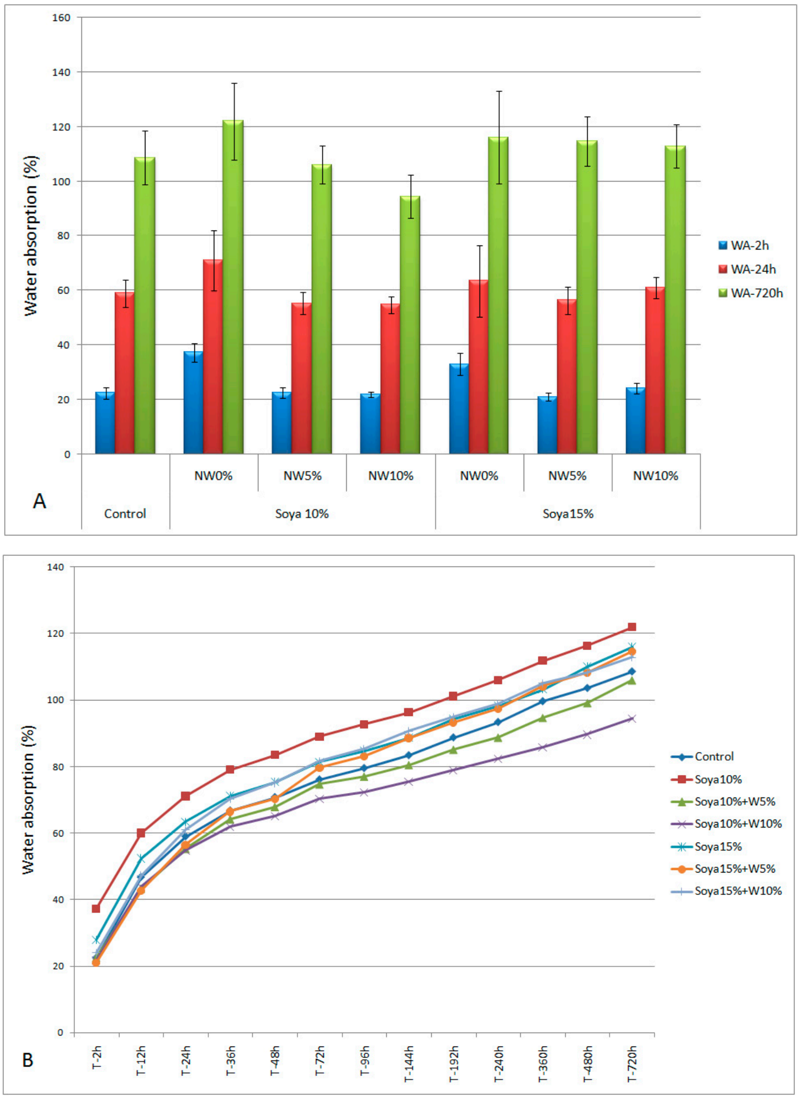


**Figure 9.** Water absorption (%) in three-layer plywood panels (Soy% = soy flour content; W% = wollastonite content; WA = water absorption).

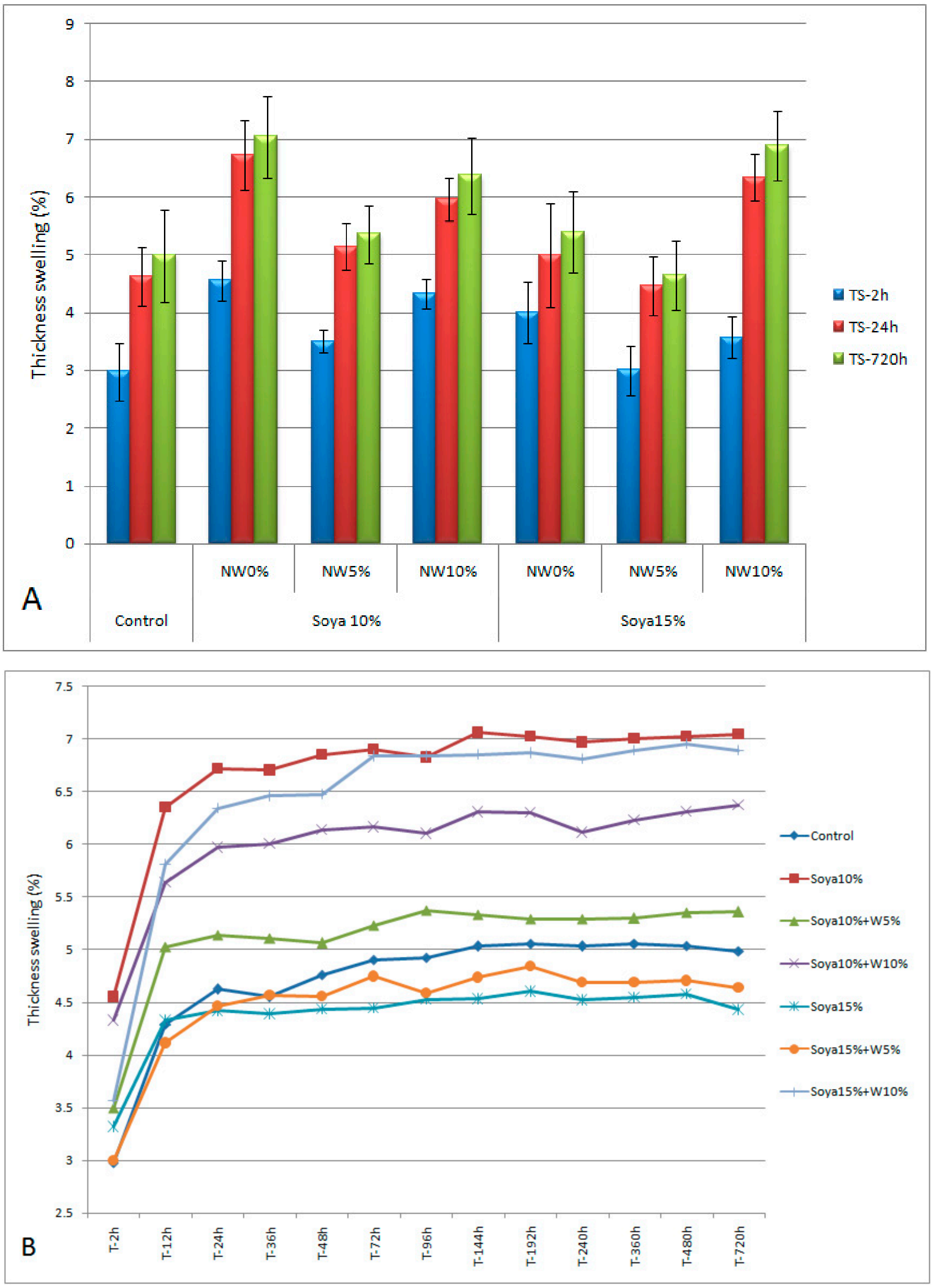


**Figure 10.** Thickness swelling (%) in three-layer plywood panels (Soy% = soy flour content; W% = wollastonite content; TS = thickness swelling).

The addition of both SF and W to UF resin resulted in a decrease in pH of the resin mixture (Table 4). Gel time was significantly increased as a result of the addition of both SF and W (Table 4); however, the gel times of all mixtures were below the hot-press time of 5 min. Therefore, it is unlikely that alterations in different properties measured in this study can be attributed to the difference in gel time. The addition of SF significantly increased viscosity, while W had a decreasing effect. The decreasing effect of W on viscosity was attributed to the water content of the W gel that was added to the resin mixture.

**Table 4.** Properties of the 12 resin mixtures used to manufacture three-layer plywood.

| Binder | pH | Gel Time (s) | Viscosity (6 rpm) (cP) | Viscosity (10 rpm) (cP) |
|---|---|---|---|---|
| UF [1] 100% | 7.4 | 75 | 449.9 | 455.9 |
| UF 95% + SF [2] 5% | 5.4 | 105 | 564.9 | 566.9 |
| UF 90% + SF 10% | 5.2 | 128 | 824.8 | 794.8 |
| UF 90% + SF 10% + W [3] 5% | 5.6 | 214 | 689.9 | 656.9 |
| UF 90% + SF 10% + W 10% | 5.2 | 230 | 569.9 | 551.9 |
| UF 85% + SF 15% | 5.6 | 146 | 1300 | 1302 |
| UF 85% + SF 15% + W 5% | 5.5 | 172 | 1120 | 1086 |
| UF 85% + SF 15% + W 10% | 5.1 | 158 | 949.8 | 902.8 |
| UF 80% + SF 20% | 5.6 | 172 | 2000 | 1911 |

[1] UF = urea-formaldehyde resin; [2] SF = soy flour content; [3] W = wollastonite content

Cluster analysis as a function of the properties measured demonstrated that control panels were remotely clustered away from panels containing soy flour and wollastonite (Figure 11). This showed the significant effect of both soy flour and wollastonite on the overall properties of plywood panels. Panels containing either 5% or 10% wollastonite were also clustered differently from those containing only soy flour, indicating the significant impact of wollastonite. On the basis of the results of each property considered individually and altogether, it was concluded that panels containing 10% soy flour and 5% wollastonite are recommended to achieve the optimum decrease in carcinogenic formaldehyde emission, as well as the optimum physical and mechanical properties. With regard to the promising results of wollastonite as a reinforcing filler in different resins and coatings, further studies can be carried out to investigate the effects of the addition of wollastonite to different wood-based composite panels produced solely using bioresins, such as soy flour.

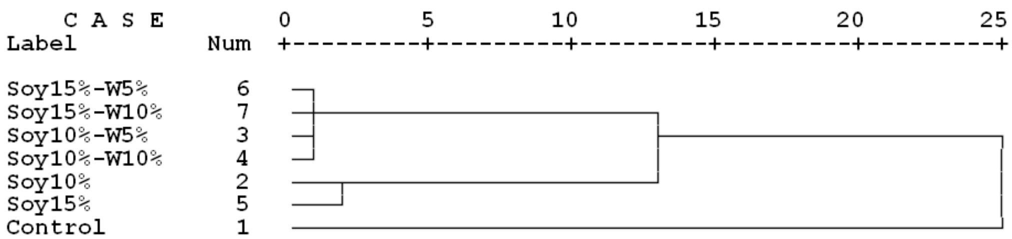


**Figure 11.** Cluster analysis of seven different three-layer plywood panels produced with urea-formaldehyde resin, and 10% and 15% soy flour substitution for UF resin, plus addition of wollastonite at 5% and 10% (Soy% = soy flour content; W% = wollastonite content).

## 4. Conclusions

Partial substitution of soy flour for urea-formaldehyde resin has the potential to decrease carcinogenic formaldehyde emission in plywood panels. Shear strength was also improved as soy flour content increased. However, this had a negative effect on the water absorption and thickness swelling of plywood panels. The addition of micron-sized wollastonite mitigated the undesirable increased hydrophilicity in panels caused by soy flour. It was concluded that 10% soy flour and 5% wollastonite provide the lowest formaldehyde emission and the most optimum physical and mechanical properties.

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