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USING NANOCLAY TO MANUFACTURE ENGINEERED WOOD PRODUCTS- A REVIEW

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ABSTRACT

Impregnation of materials using nanomaterials has been increasingly catching on and many novelty products such as automobile parts, furniture items, paint formulations, anti-microbial surface coatings, etc. have been prepared. In the wood-based industries, nanoclay is a particular nanomaterial of much significance. Different types of nanoclays, both natural and synthetic are available in the market and montmorillonite is one of the most widely used clay nanomaterials. Mixing of nanoclay in a solvent is difficult since it forms a dispersion and thus a variety of dispersion techniques were adopted. High-speed mixing techniques and ultrasonication show the most promising results to prepare nanoclay loaded formulations. These formulations could be characterized using techniques such as X-Ray Diffraction, Scanning Electron Microscopy, Thermo-Gravimetric Analysis, and Differential Scanning Calorimetry. Nanoclay use at loadings below 6% has been shown to dramatically improve the physical and mechanical properties of engineered wood products while also optimizing the pressure and temperature parameters and resin loading.

Original Article

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INTRODUCTION

Wood and woody substances are a few of the most widely used materials subject to various end uses ranging from the supporting structures of a building to the attractive furniture items within. Strict regulations regarding tree felling abound nowadays and thus lots of engineered wood products (EWPs) have been developed to replace raw wood. Engineered wood composite products such as plywood, particleboard, medium-density fiberboard (MDF), oriental strand board (OSB), laminated veneer lumber (LVL), wood-plastic composites (WPC), etc. are some of the engineered wood products that show similar and even better properties compared to solid wood. All these engineered wood panel products can be manufactured from low-quality solid wood and even waste material from various wood-based industries. These products are already much cheaper compared to solid raw wood. Adding to that, changing consumer preferences led to the price of particle boards dropping significantly (Clark, 2015). An important material required for the manufacture of such engineered wood panel products is resin. Various resin formulations have been crafted over the years. Common polymeric resins that are used in wood-based industry are polyvinyl acetate (PVA), urea-formaldehyde (UF), etc. for interior purposes and melamine-formaldehyde (MF), phenol-formaldehyde (PF), phenol urea-formaldehyde (PUF), etc. for exterior purposes. The cost of these resins

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varies from being inexpensive to being very costly. In a study conducted by Wang *et al.* (2008), it was revealed that resins constitute about 20 to 25% of the production cost in different industries manufacturing wood-based panel products. In the same study, it was also concluded that if this cost could be reduced by even 1%, then the medium-scale manufacturing units could save up to $5 million US every year.

The trend of trying to use different nanofillers along with resin formulations arose from this idea of reducing the use of resin. Nanotechnology has been reaching new heights in every sphere and its use in the wood-based industry is not surprising. Ashori and Nourbakhsh (2009) made extensive research where they have used nanoclay as filler with the resin. They found out in their study that these nanofillers played a significant role in improving the board properties while positively affecting parameters such as temperature, pressure, amount of resin used, etc. and thus lowering the overall cost of production. Such nanofillers were also not required in huge proportions but very fewer quantities concerning the dry weight of resin- less than 10% of the dry weight of the resin. At such low concentrations only, they showed great improvements in various physical and mechanical properties of the boards that were being produced. Experimental studies conducted by Zerda and Lesser (2001) and Deka and Maji (2010) on extruded thermoplastics comprising of wood flour also confirmed that small concentrations of nanoparticles in resin formulations led to better strength, toughness, and MOE in different wood-based panel products along with higher resistance to moisture absorption, heat, and flames which are known problems with wood-based products.

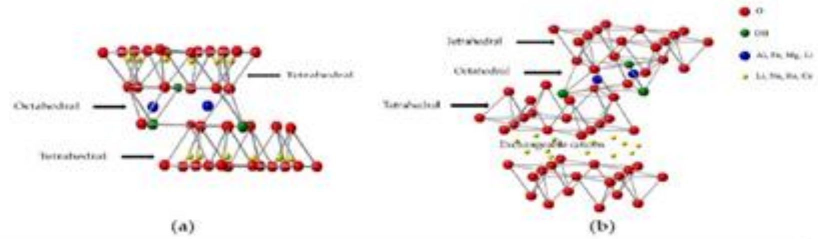
Typically, a nano particle is any particle with one of its dimensions lying in the nanoscale between 1nm and 500nm. The small size brings about an impressive feature in the nanoparticles- a very high surface area. There are different kinds of naturally occurring nanocomposite materials such as mollusk shells, teeth, bone, and even wood. These have been existing in nature for millions of years. Nanoclay too is such a naturally occurring material composed of aluminum, magnesium, and silicon minerals arranged in a layered structure. The smaller size and high surface area ensure that nanoclay has a very high aspect ratio in the range of 10:1 to 1000:1 as noted by Ashori and Noubrakhsh (2009). This high aspect ratio plays a major role in giving nanoparticles their terrific properties. However, Alexander and Dubois (2000) successfully show that these excellent properties can only be sought out only when the nanomaterials have been exfoliated or at least intercalated properly.

The physical properties and chemical behavior of nanomaterials such as nanoclay are highly different from their corresponding microparticles owing to their high surface area and high aspect ratio. These enhanced properties allow for remarkable improvements in the properties of wood panels constructed using nanoparticles as fillers. For example, a 25% increase in the wood bonding strength of urea-formaldehyde resin coupled with 1% and 1.5% nano-silica over a control mixture was observed by Lin *et al.* in a 2005 study. Similar improvements in the properties of MDF, particleboard, and plywood were also observed when they were glued using 1% nano-silica doped UF resin.

This paper discusses the use of nanoclay for the preparation of novel EWPs. There are certain restrictions on using nanoclay, the most common difficulty being mixing and not forming a homogenous solution. The prepared formulations also tend to have a very small shelf life. Researchers have tried to optimize the process but much more needs to be done before a process incorporating nanoclay use could be successfully adopted and monetized by the industries.

NANOCLAYS IN USE

Nanoclay is one of the most used nanofillers in the case of engineered wood products. The use of nanoclay is abundant since it is easily available in natural form and is also highly cost-effective. These are compounds with a layered structure with alternating tetrahedral and octahedral blocks and there are generally 3 kinds of layers available- 1:1, 2:1, and 2:1:1 (Guo *et al.*, 2018). In the 1:1 arrangement, one tetrahedral sheet is connected to an octahedral sheet and in the 2:1 arrangement, two tetrahedral sheets are connected to one octahedral sheet. The 2:1:1 arrangement shows two adjacent octahedral sheets with one of them connected to two tetrahedral sheets as remarked by Barton *et al.* (2016) and Majeed *et al.* (2013). There are mainly two categories of nanoclay available: natural and synthetic nanoclay.



Clay Layer Type	Clay Group	Clay Species
1:1	Rectorite, Kaolinite, Halloysite, Chyrsotile	Lizardite, Berthierine, Cronstedtite, Kellyite, Fraipontite, Brindleyite, Dickite, Nacrite
2:1	Smectite, Vermiculite, Pyrophylite talc, Mica, Brittle Mica	Montmorillonite, Laponite, Sepiolite, Hectorite, Bentonite, Vermiculite, Pyrophyllite, Talc, Muscovite, Paragonite, Clintonite, Bityite
2:1:1	Chlorite	Amesite, Cookeite

Figure 1: Nanoclay Crystal Structure (a) 1:1 Layered Nanoclay; (b) 2:1 Layered Nanoclay (Source: Guo et al., 2018)

Natural Nanoclay

The many naturally available nanoclays available to us are kaolinite, bentonite, laponite, vermiculite, saponite, and montmorillonite (Das *et al.*, 2019). These are generally obtained from layered sediment rocks. Such nanoclay material is regularly and widely used in various bio-composite industries to bring about an enhancement in physical and mechanical properties as well as anti-corrosion tendencies of different materials (Paras *et al.*, 2017). Das *et al.* (2017) concluded from their work that nanoclay can also have fire retarding tendencies because of their plate-like structure and anisotropic behaviors.

Synthetic Nanoclay

The synthetic variants of nanoclay are crafted from metallic oxides. At low temperatures, a hydrothermal slurry is refluxed for 10 to 20 hours (Möller *et al.*, 2010). The nanoclay particles are also produced via melt process at high temperatures of 1300ºC followed by dissolving in water for purification (Stöter *et al.*, 2013). A semi-synthetic variant of nanoclay is also available that is crafted through the substitution of groups in naturally occurring minerals such as talc (Das *et al.*, 2019).

Montmorillonite

Nanoclays vary depending upon the chemical composition as well as their crystal structures (Nazir *et al.*, 2016). Montmorillonite, named after Montmorrillon, the place in France where it was first identified, is one of the most used clay nanofillers (Turku and Kärki, 2013). These naturally occurring nanofillers are composed of a 2:1 layered structure and can be represented by the chemical structure of $M_X(Al_{4-X}Mg_X)Si_8O_{20}(OH)_4$. A schematic representation of the MMT structure is given in figure 1b. In the chemical formula, M stands for a metallic cation such as sodium (Na^+) or potassium (K^+), thus MMT is available commercially as Na^+MMT and other such formulations. The crystal structure of MMT is such that it features two tetrahedral SiO_2 stacked upon one another and fused to a layer of edge-shared octahedral alumina in between. Each of the SiO_2 layers, being composed of covalent bonds, are attracted to one other through weak van der Waal's forces of attraction. There is a space available between two stacked layers which are filled with the hydrated metallic cations (Na^+ or K^+). There are exchange sites for cations on the siloxane surface of MMT that allow it to be easily combined with a variety of organic and biological molecules (Ganguly *et al.*, 2011).

TYPES OF DISPERSION TECHNIQUES

When mixed in water or any other solvent, nanoclay forms a dispersion. Dispersion in a colloidal system and differs from solutions. A homogenous solution such as sugar and water has no phase boundary and is continuous throughout the system. A heterogeneous solution such as sand and water has two distinct phases with the solute settling down after standing and is not continuous throughout the system. A dispersion is at least a two-phase system with distinct phase boundaries. However, the particles such as mud, nanoclay, etc. do not settle down and are available throughout the continuous phase such as water, isopropyl alcohol, etc. However, in a dispersion, nanoparticles tend to form agglomerates when they are being mixed. The agglomeration of nanoparticles poses a major problem as this changes their dimension from the nanoscale to the microscale or even larger, and hence negates their astounding properties which are a result of the small size. According to Landry *et al.* (2008), the key to a great dispersion is by exfoliation of the stacked plates in a great manner. Different techniques which are used to create a nanoclay dispersion are listed as follows:

- *Manual Mixing:* Nanoclay is taken in a beaker and the necessary solvent is added to it. This mixture is then stirred manually such that the nanoclay forms a dispersion in the continuous phase. This is a very primitive method of making a nanoclay dispersion and has the lowest efficacy since the degree of agglomeration is the highest. A study conducted by Bensadoun *et al.* (2011) revealed that agglomerates as big as 10 microns could be found in a nanoclay dispersion when it was mixed using manual mixing techniques.

- *High-Speed Mixing:* Nanoclay is mixed in the solvent medium at speeds of up to 1000 rpm. However, Landry *et al.* (2008) account that such a method is not capable of producing a good nanoclay blend because it produces very low shear.

- *Ball Milling:* This procedure is an advanced form of High-Speed Mixing wherein glass beads are used in the formulation media. The glass beads further enhance the exfoliation and dispersion process but it takes as much as 2 hours for a particular formulation as conceived by Landry *et al.* (2008).

- *Mechanical Stirring/Ultrasonication*: Mechanical stirring is done using a homogenizer and the process is very similar to manual mixing. The difference is that a homogenizer rotates at very high frequencies above 10,000 rpm and has teeth that crush the intercalated nanoclay particles to keep them in nanoscale size. Ultrasonication uses high-frequency ultrasonic sound waves which are passed through the liquid media. Kaboorani *et al.* (2013) indicated that the use of alternating low- and high-pressure waves through the solvent media creates micro-bubbles. These bubbles are very short live and collapse after collision within a few microseconds. The high-speed liquid jets create high shear forces which ultimately lead to a greater degree of dispersion.

- *High Shear Mixing:* The High Shear Mixing (HSM) technique was extensively studied by Farida Bensadoun (2011) and showed very promising results. The degree of agglomeration was compared to that of manual mixing and it was observed that where manual mixing produced agglomerations of up to 10 microns, the HSM technique produced agglomerations that are smaller than 1 micron. The nanoclay owing to its smaller size and better mixing also showed a better catalytic effect which resulted in a much lower gel time (gel time was reduced to just 3 minutes from 45 minutes).

NANOCLAY-RESIN FORMULATION

The efficacy of the nanoclay-resin formulation depends on the degree of dispersion of the nanoclay particles. A higher dispersion directly leads to a higher enhancement in the properties of manufactured wood panel products. Xian *et al.* (2013), remarked that the platelet separation was affected by various factors such as the mixing time, chemistry of the resin, the method employed for mixing, pretreatments of the nanoclay. Pavlidou and Papaspyrides (2008) illustrated that there are three methods for proper dispersion of nanoparticles:

- ***Exfoliation****:* A method wherein complete separation of the platelets occurs leading to a homogenous dispersion.
- ***Intercalation:*** The polymeric resin intrudes into the space between the platelets leading to a higher distance between them, their platelets are, however, stacked together, parallel to each other.
- ***Phase Separation*****:** The nanoclay particles are dispersed in the solvent or polymeric resin medium but they are grouped such that the resin cannot even intrude within the layers.

In addition to this Alexandre and Dubois (2000) stated that nanoclay has to exfoliate or at the very least intercalate into the resin for an effective formulation. Lei *et al.* (2008) observed that Na^{+}MMT was easily exfoliated in the acidic medium of UF resin indicating that resin chemistry played a very important role in the dispersion of resin in the medium.

CHARACTERIZATION OF NANOCLAY-RESIN MIX

Characterization techniques are analysis techniques that are used to understand the structure of a compound at molecular or even atomic levels. These techniques give us various graphs (DSC, TGA, XRD, etc.) as well as pictorial representations (SEM, TEM, etc.) which indicate the structural behavior of the compounds. When nanoclay particles are added to a resin, it has to show some change at the molecular or atomic level which ultimately leads to the enhancement of characteristics. These kinds of changes are also very easily observed using such characterization techniques.

Munoz and Moya (2018), carried out SEM analysis on plywood samples. A smooth surface was obtained by cutting through an ultramicrotome to conduct the SEM analysis. They were successfully able to determine the thickness of the glue line using SEM analysis. SEM analysis may also be carried upon the resin-nanoclay formulation to get an idea about intercalation or exfoliation of nanoclay into the resin. Wang *et al.* (2017) evaluated the morphology of PF and PF loaded with nanoclay and successfully established a difference in them.

X-Ray Diffraction is also an impressive method to understand the chemical composition of different nanoclay-resin mixes. They help determine the curing tendencies of a resin impregnated with nanoclay. Lei *et al.* (2008) remarked that an X-Ray diffraction study is useful in understanding the degree of intercalation of nanoclay. Wang *et al.* (2017) also used XRD analysis to determine the crystalline structure of resin loaded with nanoclay to identify if there was any change in the structure. Bragg's Law is used to determine d-spacing when XRD analysis is used which leads to an idea about the degree of intercalation or exfoliation.

Thermo Gravimetric Analysis methods are an important way to understand the components of any formulations. The sample material is constantly heated to high temperatures while constantly being weighed. The analysis is carried on between a range of temperatures with the temperature increasing at regular intervals. Wang *et al.* (2017) analyzed 50ºC to

600ºC in a nitrogen atmosphere and the modified composites showed much better stability as compared to non-modified composites. Manocha *et al.* (2008) found out 3 distinct peaks at different temperatures indicating different things- at less than 200ºC it indicated the loss of free water, between 200º and 500ºC it indicated the loss of volatile organic compounds, and above 500ºC up to 800ºC it revealed the loss of structural water. DSC analysis is another kind of characterization technique using heating methods. This method is useful in determining the melting point, glass transition temperature, and so on. According to Mamatha *et al.* (2015), DSC analysis is useful in determining the curing behavior of resin with increasing temperature.

EFFECT OF NANOCLAY ON PROPERTIES OF PARTICLEBOARD

Particleboard is a kind of engineered wood panel product that is manufactured from shavings, splinters, flakes or silvers of wood, or appropriate lignocellulosic material. Appropriate sizing of the "particles" is done before the addition of the resin. The resin is generally added after drying the particles by spraying while the particles are placed in a rotary drum and rotated to mix with the resin. The water content of the resin should be such that it does not inadvertently affect the moisture content of the particles. After mixing with the resin the whole mass is placed in a mold to form mats which are then placed under a hot press for a specified duration of time at a specified temperature. The density of particleboard should lie in the range of 500 to 900 kg/m^2 and its moisture content should remain between 5% and 15% according to IS 3087:2005.

Mechanical Properties of Particle Board

Hosseyni *et al.* (2014) used nanoclay loading at 3% and 6% with urea-formaldehyde (UF)(10%) and isocyanate (MDI)(4%) resin blended by stirring at 5500rpm (3% and 6% nanoclay loading) and ultrasonication (3% nanoclay loading). All the UF boards showed a higher Modulus of Rupture (MOR) which is a major property to determine wood bonding capacity. The use of a 3% ultrasonicated nanoclay in MDI showed a 33% increase in MOR values compared to the control setup. A similar observation was also made by Ismita and Lokesh (2017) when they prepared particleboards with 2%, 4%, and 6% nanoclay loading. The 6% nanoclay boards showed MOR which was higher by 34% compared to the control setup with 0% nanoclay loading. Even the 2% and 4% nanoclay loaded boards showed a higher MOR compared to the control setup. Salari *et al.* (2012) also reported a higher MOR value of boards with a nanoclay loading of up to 5%.

Modulus of Elasticity (MOE) is another indicator of the strength properties- it shows how much solid material is capable of resisting elastic deformation. Hosseyni *et al.* (2014) found that MOE values also increased with increasing nanoclay concentrations in the resin and it increased by up to 73% for 6% nanoclay loading in UF. Boards loaded with MDI at 6% loading did not show a similar change in properties indicating that the loading might be too high (Hoseyni *et al.*, 2012). Candan *et al.* (2015) observed no significant change in MOE values on adding nanoclay fillers to the resin blend. Ismita and Lokesh (2017) prepared particleboards wherein 6% nanoclay loading showed an increase of up to 65% in MOE values and ANOVA revealed that all the MOE values were significantly different from the control setup.

The Internal Bonding (IB) strength also varied due to the addition of nanoclay. Ismita and Lokesh (2017) observed that 2% nanoclay loading was effective in enhancing the IB by about 18%, though the increase was not so effective in higher concentrations (4% and 6%). Hosseyni *et al.* (2014) also revealed that the IB strength increased or remained constant on the addition of nanoclay. Even Lei *et al.* (2008) observed that the IB values showed a maximum increase at 2% and small improvement from a control setup up to 8% nanoclay loading. Mamatha *et al.* (2015) used nanoclay loading of up to 0.5% and revealed that the addition of nanoclay did not improve MOE, MOR, or IB strength values. They, however, had a pronounced effect on the board's resistance to white-rot fungi.

Physical Properties of Particle Board

The physical properties of particleboard include such features as water absorption and thickness swelling. These are important properties to consider as wood is a hydrophilic material and is prone to attract moisture. The resins used also have hydrophilic centers that can easily bond with water. The water-absorbing capabilities of wood make it susceptible to microbial degradation and dimensional instability.

Using nanoclay with the resin affects these physical properties of wood and wood-based panel products. In the study conducted by Hosseyni *et al.* (2014), it was observed that the water absorption capabilities of wood particles and resin were considerably reduced. Though the effect of the addition of nanoclay at 3% and 6% was not statistically significant, they still inhibited water absorption in particleboards manufactured using UF resin. Particleboards impregnated with MDI did not show much difference in moisture absorption capabilities. Ismita and Lokesh (2017) also observed that there was no statistically significant change in water absorption capabilities though it reduced by 38% to 46%.

Thickness swelling (TS) of particle boards on the other hand saw a significant reduction in nanoclay addition. It is believed that nanoclay particles can reduce the porosity of wood fibers and in turn prevent moisture from seeping into them. Ismita and Lokesh (2017) observed with only 2% loading that TS was reduced by up to 62%. Even Hosseyni *et al.* (2014) observed that TS was reduced by 36% by adding 3% nanoclay. They did not find any noticeable change with MDI since the resin itself is moisture-resistant.

EFFECT OF NANOCLAY ON PROPERTIES OF MEDIUM-DENSITY FIBERBOARD (MDF)

Medium Density Fiberboard is constructed from wood or appropriate lignocellulosic materials which are cut or chipped into smaller pieces by passing it through a chipper machine. MDF is different from particleboard in the fact that it uses smaller-sized wood fibers, unlike particle boards which can even be manufactured from wood dust. According to the IS 12406:2003, the chipped fibers are first steamed and defibrated (a procedure to soften the lignin in fibers) and then dried. They are then blended with resin, formed into mats, and pressed under a press at control temperature and pressure for a specified duration.

Mechanical Properties of MDF

The mechanical properties of MDF are comparatively lower than that of solid wood but should be similar to that of particle boards. MDF is used for finer furniture products while particle boards are used for low furniture products, underlayment while flooring, as a substrate to kitchen countertops, and so on. Keeping this in mind, particleboard and an MDF should have similar values of MOR, MOE, and IB strength.

Omrani *et al.* (2018) conducted a test wherein wood fibers were blended with PF and UF resins and the chicken feather was used as a filler material for the construction of MDF. They also used nanoclay with the resins to test its efficacy in improving the properties of MDF. The MOR of MDF manufactured with 100% wood fibers and blended with UF increased by about 10%. However, a similar change was not observed for PF blended wood fibers or MDF with chicken feathers as a filler material. Taghiyari *et al.* (2014) used various concentrations of nanowollastonite up to 8% and observed that the MOR increased with each higher loading of the nanoparticle. This MOR value was higher by up to 45%

from the control setup. Taghiyari *et al.* (2015) conducted a similar test wherein nanowollastonite was used both on the surface and internally. It was recorded that the surface application also showed an impressive increase in MOR values. Ashori and Nourbakhsh (2009) found out that the using nanoclay loading of 6% improved the MOR by 20% when MDF boards were prepared by pressing at 175ºC and by 9% when pressed at 165ºC. they also found out that the MOR gradually increased with increasing nanoclay loading up to 6% and then decreased drastically at 8% nanoclay loading.

A similar trend was noted by Ashori and Nourbakhsh (2009) in their experiment in the MOE values also. The MOE increased by about 10% to 35% on increasing the nanoclay concentration from 2 to 6% but decreased drastically at 8% loading. Taghiyari *et al.* (2014) found out that on increasing nanowollastonite loading, the MOE increased by up to 32% from the control setup. The MOE also increased gradually on increasing the nanofillers loading.

The IB strength values were also impacted by the nanofiller concentration according to various studies that were conducted. However, it did not show a consistent trend of increasing or decreasing with increasing nanofiller concentration. According to Ashori and Nourbakhsh (2009), the highest IB strength was observed at 4% nanoclay loading which was 36% higher than the control setup. The lowest IB strength was noticed at 8% nanoclay loading which was lower by 4% than the control setup. Taghiyari *et al.* (2014) showed a consistent increase in IB strength with increasing nanowollastonite concentration from 2% to 8% with the highest value being 85% greater than the control setup. This could be attributed to enhanced heat transfer properties which led to better conduction of heat to the core and hence better bond formation during hot pressing.

Physical Properties of MDF

The physical properties of the MDF panel, namely water absorption (WA) and thickness swelling (TS) depend as much on the nanoclay loadings as it depends on the type of resin used. Omrani *et al.* (2018) constructed MDFs using a wood fiber and chicken feather blended with UF and PF resin and directly observed this behavior. The panels that were manufactured using PF resin showed much lower WA compared to panels made using UF resin. This was possible because PF itself is resistant to moisture uptake as it is hydrophobic. The addition of nanoclay further reduces the WA properties of both UF and PF blended MDF. The TS follows a similar trend as WA as the lower the amount of water absorbed, the lower will be the dimensional instability.

Ashori and Nourbakhsh (2009) showed that there is a relation TS with the pressing temperature. In their study, boards were prepared at 165ºC and 175ºC and the latter boards showed lower TS. The TS also decreased with increasing nanoclay concentration and at 8% nanoclay loading, it was as low as about 16% (20% lower than the control setup). The WA also showed a similar trend and was lowered with increasing nanoclay concentration. When Takhiyari *et al.* (2014) used nanowollastonite the WA showed a slight increase but TS, on the other hand, showed a slight decrease; though no statistically significant change was observed in either property.

From various studies conducted over the years, it can be understood that using nanoclay or other nanofillers does affect the properties of MDF. The use of nanoclay at a very high concentration may not be the best choice but optimum use of nanoparticles to craft MDF shall lead to the production of a better quality of MDF.

EFFECT OF NANOCLAY ON PROPERTIES OF PLYWOOD

Plywood is a kind of engineered wood panel product that is designed with the idea of having uniform strength throughout in all directions. A piece of solid wood has different strength properties in longitudinal, radial, and transverse directions but there is uniformity in strength in different directions in plywood. To manufacture plywood, veneers with a reasonably smooth surface are produced from logs either by a rotary cutter or through slicing. As per the IS 303:1989 regulations, these veneers are treated with preservatives in wet conditions only or after they are converted onto plywood. The treated veneers are dried and glue is applied to its face. The glued veneers are then placed one upon the other with the grain direction of adjacent veneers at right angles to one another. They are then pressed at specified conditions of temperature and pressure for a specific duration. The surface of the obtained plywood has to be reasonably smooth and may even be smoothened through sanding. It should also be remembered that the grain direction on the faces should be parallel to the longer side and each other.

Mechanical Properties of Plywood

Since plywood has visible grain patterns, its mechanical properties vary along and perpendicular to the grain. The mechanical properties also depend chiefly on the specific gravity (SG) of plywood and hence on the species used to develop the plywood boards. *C. alliodora* having a higher SG (0.46) showed much higher values for mechanical properties compared to *V. ferruginea* (0.35) when plywood boards were made. When nanoclay was added, a loading of 0.75% showed the best properties of mechanical strength (MOE and MOR) both parallel and perpendicular to the grain (Muñoz and Moya, 2018).

Doosthoseini and Zarea-Hoseinabadi (2010) observed that the addition of nanoclay did not have a statistically significant effect on MOR or MOE either parallel or perpendicular to the grain. However, increasing nanoclay loading up to 5% with MUF resin improved the MOR face grain perpendicular to the span. Lei *et al.* (2008) tried to observe the effects of nanoclay loading between 2-8% and saw that the MOE increased with increasing temperature on adding nanoclay. The highest readings were obtained for 4% nanoclay loading and then the MOE values started decreasing, though it was higher than the control specimens with % nanoclay loading. Ismita *et al.* (2019) correlated the effects of pressing at different pressure with different nanoclay loadings. The MOR parallel to the grain was similar for different pressures (14 kg/cm^2 and 21 kg/cm^2). The MOR values did not vary much compared to the control specimens but were considerably lower at 5% loading. The MOR perpendicular to grain gradually decreased with increasing nanoclay loading as well as increasing temperature. The MOE on the other hand slightly increased with increasing the pressure but the addition of nanoclay did not have any significant effect on it.

Bond Strength of Plywood

The bond strength is an important characteristic for plywood boards as it determines how well the adjacent layers of veneers have bonded with one another. A higher bond strength ensures better mass distribution within the plywood and hence leads to a better quality of plywood. Ismita *et al.* (2019) observed that the glue shear strength improved with increasing the pressing pressure. The addition of nanoclay did not show any statistically significant change in the glue shear strength but it was higher than that of the control specimens. The observation was similar when glue shear strength was calculated in the wet state.

Doosthoseini and Zarea-Hoseinabadi (2010) also observed that nanoclay loading did not have much effect on internal bonding strength. Muñoz and Moya (2018) concluded that the glue bond strength depended on the species of trees that were used to construct the plywood boards. The bond strength increased with the addition of nanoclay filler but the highest increase was observed for *G. arborea* (SG=0.41) at 2% nanoclay loading (85% higher than the control specimen).

Wang *et al.* (2017) found out that the bonding strength of untreated resin decreased by about 48% when it was soaked in boiling water cyclically. This decrease was much reduced when nanoclay fillers were used which shows that nanoclay inculcates successful barrier properties in the bond line.

Physical Properties of Plywood

When discussing plywood, the density or specific gravity of plywood is as important as its water absorption and thickness swelling. The density and specific gravity are important physical properties for plywood as it depends entirely on the type of species used (Shukla and Pascal, 2008) and also, at times, on the process parameters. Because of its dependence on species used, it is even recommended that a particular board of plywood is made from the same part of a tree (i.e. either sapwood or hardwood) to maintain the uniformity in strength properties.

Muñoz and Moya (2018) observed that the SG or density of individual tree species is very important when manufacturing plywood. They used veneers from different tree species and found that veneers from *C. alliodora* (SG=0.46) formed plywood with the highest SG. Similarly, *V. ferruginea* (SG=0.35) plywood had the lowest specific gravity in their study. The presence of nanofillers such as nanoclay further increased the SG of plywood but that was attributed to the added mass because of the presence of nanofillers. The water absorption and thickness swelling tendencies of plywood were modified and considerably lowered due to the presence of nanoclay. Doosthoseini and Zarea-Hosseinabadi (2010) and Lei *et al.* (2010) also made similar observations concerning plywood manufacturing.

Lei *et al.* (2010) hypothesized that the improved properties of WA and TS were observed because nanoclay itself was water repellent and hence contributed majorly to reducing the hydrophilicity of wood as well resin. Doosthoseini and Zarea-Hosseinabadi (2010) also concluded that resin played an important role in determining moisture absorption tendencies. If hygroscopic resin such as MUF was used, then the overall water absorption was less for manufactured plywood compared to UF resin which is hydrophilic. This is further facilitated by the use of nanoclay in the resin and it was successful in enhancing water repellent properties in both resins.

CONCLUSIONS

Nanoparticles such as nanoclay have shown impressive improvements in the property of engineered wood products. The small size ensures a high surface area and a high aspect ratio which are directly responsible for the tremendous effects of nanoclay. It has been noted that using nanoclay in higher loadings such as 8% () and 10% () does not show enhancement in physical properties. This is probably due to the higher agglomeration of nanoclay particles.

Wood-water relation is another interesting aspect of EWPs which is affected by nanoclay addition. The resin also plays quite a significant role and there is a need to understand the nanoclay-resin chemistry further to develop better products.

The pressure and temperature parameters are also affected by nanoclay addition. Optimizing the pressure and temperature parameters and lowering them to get better EWPs could be a turning point for industries. It will optimize the cost of production while also bringing in increased profits because of the better-quality product.

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