

Research Article

Properties of Sago Particleboards Resinated with UF and PF Resin

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The sago processing industry in Mukah, Sarawak, had generated huge amount of sago waste after the milling process and scientists have employed the waste into composite material. In this work, sago residues were mixed with the Phenol Formaldehyde (PF) and Urea Formaldehyde (UF) for particleboard fabrication. The fabrication and testing methods are based on JIS A 5908 Standard. A single layer particleboard using sago particles was fabricated at targeted density of 600 kg/m³. Particles with weight fractions of 90%, 85%, and 80% with two different matrices were used in the fabrication. The results demonstrated that the samples with different weight fraction and matrix have great influence on the mechanical properties such as MOR, MOE, Young's Modulus, tensile strength, impact strength, screw test, and internal bonding. The sago UF/PF particleboard only displays single stage decomposition. All the panels underwent physical tests which are water absorption and thickness swelling. The combination of sago particles with UF/PF can be utilized for general indoor application purposes such as furniture manufacturing. Sago particleboard made by UF/PF provided the advantages like optimized performance, minimized weight and volume, cost effectiveness, chemical resistance, and resistance to biodegradation.

1. Introduction

The demand of wooden materials has grown over the years with the increasing of population and new application area [1]. This had caused significant pressure on the forest resources and the cost that leads to high demand. To overcome the problem, researchers had found an alternative using the agrofibres combined with thermoplastic or thermoset as composites to replace wood supply [1]. Agricultural material or biomaterial plays an important role in the composites and furniture industries. Using natural fibres as reinforcing agents in composites contributes to a positive environment where raw materials are fully utilized [2]. Bioresources have provided us with the advantages like multifunctionality in application, flexibility in characteristics, lower production cost, biodegradability, and wide distribution all over the world [3, 4]. Natural fibres such as jute, hemp, kenaf, sisal, and rice husks have been investigated for use in the composites industries due to their advantages [3].

Research found that a large amount of binder is being used in particleboard fabrication which accounts for up to 32% of the manufacturing cost [5]. Various types of binders have been used in the manufacture of particleboards. The binders are classified as interior or exterior use based on the requirement and their response to moisture and temperature. Recently, the researchers had mentioned that binders such as Urea Formaldehyde (UF), Phenol Formaldehyde (PF), Phenol-Resorcinol Formaldehyde (PRF), and Melamine-Formaldehyde (MF) were used in the particleboard fabrication [5].

In Sarawak, approximately 7 tons of sago pith waste was produced per day from a single sago starch processing mill [6]. The residues from its production were discharged into the river, burnt in field, or deposited in factory compound which can lead to serious environmental problems. Safe disposal system or converting this waste into a useful product is a possible way for controlling the pollution and partial substitution of raw materials in industrial application.

TABLE 1: Specification of UF.

Table UF resin	Solid content 51.5%
UF appearance	White & opaque
Viscosity @ 30°C	168 CPS
Specific gravity @ 30°C	1.198 g/cm ³
pH @ 25°C	8.0
Solid content (3 hrs @ 105°C)	51.5%
Gel time @ 100°C	41 Sec
Free formaldehyde	1.23%
Water tolerance @ 30°C	197%
Tensile strength (≥ 0.7 N/mm ²)	1.8 N/mm ²

Sago palms are from the species of the genus *Metroxylon* which belong to the Palmae family and are rich in starch [6]. The advantages of using sago palms in material industry are that they are economically acceptable, relatively sustainable, environmentally friendly, uniquely versatile, and vigorous and promote socially stable agroforestry systems.

Therefore, it is interesting to convert the sago residues into durable products like particleboard. The objective of this study was to use waste fibres combined with the resin for manufacturing the particleboard and study the effect of UF and PF matrix on the mechanical, physical, and thermal properties.

2. Material and Methods

2.1. Material. The sago particles were obtained from Mukah and used as the raw material in the sago UF/PF particleboard. The particles were screened on a vibrator screen (Model number GM/ZTS-7A) and only particles with sieving size 1.18 mm were retained to be used in UF/PF particleboard fabrication. The output of the sieving particles was cross-checked by HIROX KH-8700 microscope. After the sieving process, the particles were subjected to the drying process under the sun for 2 days and dried in the oven at 105°C for 24 hours to achieve moisture content of less than 5%. Urea Formaldehyde (UF) with resin content of 51.5% was obtained from Hexzachem Sarawak Sdn. Bhd. and Phenol Formaldehyde (PF) was obtained from Bintulu Adhesive & Chemicals Sdn. Bhd. Both matrices were used as the binder. 1% of NH₄Cl was mixed with UF during the mixing process and acted as the hardener. The specification for both the UF and the PF matrix was showed in Tables 1 and 2 to fulfill the Japanese Agriculture Standard: 2003.

2.2. Particle Geometry Characterization. Based on pilot experiment, particles with sieving size 1.18 mm gave the highest internal bonding and screw test of the final particleboard in comparison with several sieves of different sizes utilized during trials [7]. The results had shown that the particles with less than 1.18 mm sieving size have the highest internal bonding and screw test because the particles have better bonding with matrix in the particleboard and had filled up the voids and increased the mechanical strength. In this study, the particles were sorted by the vibration sieve to the desired

TABLE 2: Specification of PF.

PF resin	Solid content 41%
UF appearance	Dark red
Viscosity @ 30°C	90 CPS
Specific gravity @ 30°C	1.191 g/m ³
pH @ 25°C	13.26
Tensile strength (≥ 0.7 N/mm ²)	1.1 N/mm ²

TABLE 3: Percentage of particles and the dimensions.

Sieving size	Group	Size range	Count	Percentages (%)
			1.18 mm	
1.18 mm	G1	0.4 mm–0.5 mm	65	32.5
	G2	0.51 mm–0.60	70	35
	G3	0.61 mm–0.7 mm	52	26
	G4	0.7 & above	13	6.5

particle size and were cross-checked by the HIROX KN-8700 (3D digital microscope). The dimension of the particles has a great influence on the final product. The sorting process gives particular effect when applied as raw material for the particleboard production as the high performance of mechanical and physical properties on the particleboard can be achieved by an optimal size of the particles. The data were taken from a random selection with 200 units of particles for 1.18 mm sieving size. There were four different sizes of particles that fall under 1.18 mm sieving size. The particles dimensions and percentage were showed in Table 3.

2.3. Panel Manufacturing. Single layer panels were manufactured using sago particle, Urea Formaldehyde (UF), Phenol Formaldehyde (PF), and ammonium chloride (1 wt% NH₄Cl) as a hardener. The preparation of the board depended on the sieving size and weight fraction. The target density was set at 600 kg/m³. The sago particles were weighted based on the desired weight and blended with UF or PF resin in a rotating mixing drum fitted with a pneumatic spray gun. The capacity of the mixture was 3.00 m³ with diameter of drum of 1.95 m. The rotating speed of mixer was 800 rpm. The cover of the drum was designed to have few small holes, each with a diameter of 1 mm. The holes released pressure during the mixing process. The main purpose of using the mixing drum was to make sure that the mixing was done evenly and to avoid the spot occurrence on the particleboard. The sago particles were mixed by spraying them with desired matrix and hardener to achieve a homogeneous distribution on particles.

After the blending process, the materials were placed into a wooden box with the dimension of 30 cm × 30 cm and manually formed as a mat. The distance bars were placed at both sides of the mat in order to get the targeted board thickness. The mats were prepressed manually to consolidate the thickness and compressed using the hot press machine at 160°C with pressure of 40 bars for 2 minutes and it gradually reduced to 20 bars and 10 bars for 2 minutes, respectively. The final dimensions of the boards were 40 cm × 40 cm × 1 cm. The panels were conditioned at 20 ± 2°C and 65 ± 5%

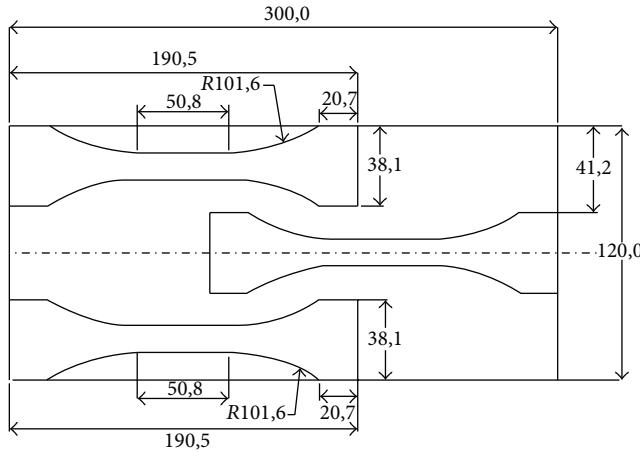


FIGURE 1: Tensile specimen, all the dimensions in mm.

relative humidity for 2 days and then cut into test specimens according to the test piece dimension. Six specimens were tested for each mechanical and physical property and the average results were reported.

2.4. Sample Preparation. The sample will be prepared based on the proportion 10 wt% of matrix mixed with 90 wt% of sago particles, 15 wt% of matrix with 85 wt% of sago particles, and 20 wt% of matrix with 80 wt% of sago particles. Urea Formaldehyde and Phenol Formaldehyde will be used in this experiment. Three variable factors were taken into account: sago weight fraction and UF and PF matrix weight fraction.

2.5. Mechanical Test. Japanese Industrial Standard (JIS A 5908) for particleboards was used to evaluate the properties of the sago particleboards [8]. The tensile specimens (see Figure 1) were prepared based on the dimension requested by the standard and the tests were conducted at 10 mm/min loading speed based on the JIS A 5908 Standard.

Tensile tests were carried out using Instron Universal Testing Machine (Model 5566). For the Charpy impact test, specimens were prepared based on the ASTM A370 standard with the width, length, and thickness as 10 mm, 55 mm, and 10 mm [9]. The impact strength of the particleboards was measured using 50 J Charpy impact tester LS-22 006. Three specimens with the measurement of 10 mm × 50 mm × 150 mm were prepared for three-point bending at 10 mm/min loading speed. Three of 50 mm × 50 mm × 10 mm size test specimens were prepared from each sample board for internal bonding and screw test. Specimens for internal bonding and screw test were tested using Instron machine with a loading speed of 2 mm/min.

2.6. Physical Test. Water absorption and thickness swelling of panels were carried out by JIS A 5908 specification. The specimens with dimension 50 cm × 50 cm × 10 cm were immersed in distilled water at 25°C for 2, 24, and 48 hours. The samples were removed from the water at different time intervals and weighted with precision of 0.001 g.

Water absorption (%) is as follows:

$$\text{Water absorption } (\%) = \frac{W_f - W_i}{W_i} \times 100\%, \quad (1)$$

where W_i is initial weight W_f is final weight.

Thickness swelling (%) is as follows:

$$\text{Thickness swelling } (\%) = \frac{T_f - T_i}{T_i} \times 100\%, \quad (2)$$

where T_i is initial thickness T_f is final thickness.

2.7. Thermal Analysis

2.7.1. Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). Small test pieces were cut from the UF/PF sago particleboard and grounded in a wood pellet mill machine (YSKJ-120) as powder. The powder sample of particleboard was prepared and tested using TGA/DSCI STAR System and Mettler Toledo thermal analyzer according to ASTM E1131. Approximately 10 mg of the powder sample was placed in an aluminium pan and heated constantly at a rate of 10°C/min from 50°C to 800°C under 30 mL/min of nitrogen gas atmosphere. The weight loss and temperature were recorded and analyzed to determine the following TGA parameters: weight loss %, initial degradation temperature, volatiles in sample, and residual weight %. DSC was used to measure all the chemical and physical changes that occurred in the sample and provided the information about the exotherms and endotherms.

2.8. Morphology Test. The Scanning Electron Microscopy (SEM) JSM-5300LV technique was used to study the fracture surface of the specimens. The SEM was operated at an accelerating voltage of 1–5 kv and emission current of 47 μA. The fracture surfaces were sputter-coated with gold of approximately 50 nm in thickness. The scanning data were analyzed at magnifications of 100x and 200x. The failed composite specimens were examined to observe the morphology of fracture surface of the particleboard, such as the interfacial interaction between the sago fibre and Urea Formaldehyde.

3. Results and Discussion

3.1. Mechanical Test

3.1.1. Bending Strength (MOR). Figure 2 illustrates the relationship between the bending strength of different types and loading of matrices applied to the particleboard. The results show that UF and PF improved the bending strength when applied to the particleboard. The bending strength of sago UF/PF strongly depends on the bonding strength between the polymer matrix, surface topology, and lignocellulosic of sago particles [10].

The flexural strength of UF particleboards increased with the resin content up to 15 wt% but decreased beyond their

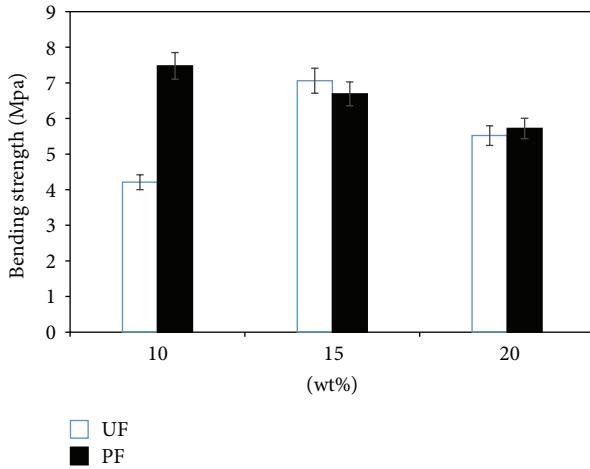


FIGURE 2: Bending strength of sago particleboard versus resin matrix content (wt%).

optimal value [11]. The excess resin beyond 15 wt% loading had reduced the strength and made the particleboard become brittle [11]. The agglomeration of sago particles at higher loadings of matrix had decreased the reinforcement-matrix bond hence lowering the magnitude of MOR [10, 12]. As a result, it led to poor interfacial bonding between the fibre and matrix hence decreasing the MOR.

The increment of UF loading from 10 wt% to 15 wt% enhanced the bending strength. This was because the 15 wt% of UF loading had more particles that were well-bonded with the matrix which reduced the voids between sago particles [13]. Due to the good intercalation of UF matrix and sago particles, the stress transfer between the matrix and fibres increased and, therefore, the bending strength improved especially at 15 wt% [14].

10 wt% of PF has better bonding between the matrix and sago. The good wetting of the sago particles by the PF matrix had formed good chemical bond between the particles and matrix, which resulted in better bending strength [10]. The sufficiency and effectiveness of the matrix in covering the surfaces of the particles had created the cross-link between the matrix and particles for better mechanical bonding throughout the hydrogen and covalent bonds [15]. PF created a better mechanical interlock between the filler and matrix particles. When PF was applied on the sago particles, the matrix penetrated easily into them and filled up the pores of the substrate. This led to better impregnation process that forced the PF to locate in particles structure and provided more resistance to shear forces when the test was conducted.

20 wt% of PF did not improve the bending strength because the excessive matrix evaporated during the hot press and the lower viscosity (90 CPS) and solid content 41% of PF caused the matrix to flow through rather than bond with the particles. In fact, PF resin contained higher amount of water compared to UF resin. Therefore, during the curing process, the moisture in PF resin evaporated more slowly compared to UF resin and, thus, PF had lower bending strength than UF. In this case, higher temperature or longer heating time

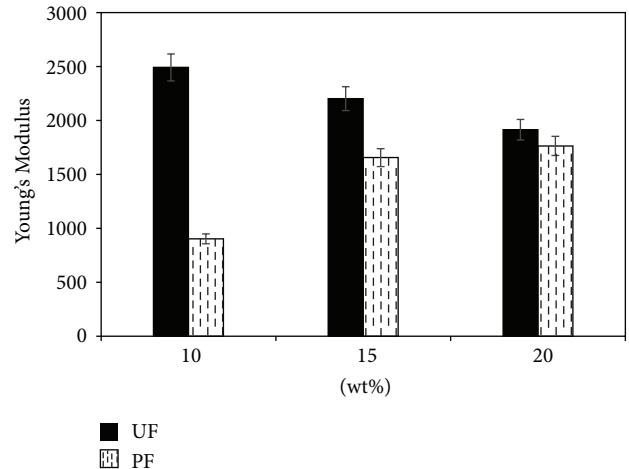


FIGURE 3: Young's Modulus of sago particleboard versus resin matrix content (wt%).

was needed for better strength bonding between particles and matrix.

3.1.2. Young's Modulus (MOE). Figure 3 illustrates the effect of UF and PF with different weight fraction on MOE. It was observed that MOE were influenced by particles/matrix interface bonding, transverse cohesion, and the perfect dispersion of individual particles [16, 17].

UF composite had better MOE compared to PF. This was due to lower viscosity in PF with longer time to complete polymerization during the hot press process [18].

Particleboard with 10 wt% of UF had the highest MOE value. The presence of polar group in the UF contributed to electrostatic absorption between the UF and sago particles. Higher electrostatic charges acting on UF or sago surface strengthened the UF/sago interface by holding them together and increased their resistance to deform [11, 19]. The modulus increased as the particles concentration increased due to deduction of the voids in the particleboard and created better bonding of particle with matrix in the board [20].

The MOE reduced by increasing the weight fraction of UF. This was because the stress transfer between particles and matrix interface reduced due to high moisture content when the matrix loading had increased [21].

Based on the results, UF particleboard exhibited higher MOE, thus, being stiffer than the PF particleboards. The interparticle bonds formed by the resins showed greater tendency of stretching due to slippage in PF resin. This indicated that more energy was required to deform the UF particleboard compared to the PF particleboard [5]. The UF filled the lumen and wall, hence forming a rigid cross-linked polymer which resulted in the increasing of the strength and stiffness [22]. Besides, MOE had increased the stiffening effect of the granules from sago [23]. Further increasing the UF loading reduced the MOE because the sago had reduced. The starch granules from sago were stiffer than the matrix when dispersed at sample (90 wt% sago + 10 wt% UF matrix).

10 wt% of PF showed the lowest MOE and it tends to be ductile. This was due to shortage of PF matrix to bond all the particles in the board [20]. By increasing the weight fraction of PF, the MOE increased. This was because the covalent bonds acted to connect the PF to the sago which helped to fill the gap between sago particles [13].

PF resin had lower MOE value compared to UF because of the acidic properties of sago which resulted in weakening in adhesive bonding strength [24]. The average pH of sago was between 3 and 5.5 [25]. The strength of bonding could be reduced as the temperature or chemical reaction between the PF and sago particles decreased. In general, with natural fibre exposed to an acid or base for a longer time or higher temperature, the strength could be degraded. Besides, sago particles with high buffering capacity would require the addition of catalyst to bring the pH to the level (acidic or alkali) for optimum resin curing. This will increase the good interlinks between matrix and particles [26]. UF adhesive had better bonding than PF because the NH_4Cl was applied during the fabrication process that increased the bonding quality as compared with noncatalyst on PF. The catalyst and sago particles acidity could increase the curing rate [27]. The curing rates of formaldehyde-based resins were dependent on the pH of the catalyst in which they cure. The low pH could cause precuring and the board would become weak and flaky due to the binder cures before the particles had been compressed and when the press closed the procured resin bonds were broken [24, 27].

3.1.3. Internal Bonding (IB). The specimens were prepared based on the JIS A 5908 with the width of 50 mm \times length of 50 mm \times thickness of the board. The specimens were first glued to the aluminium blocks on both surfaces by using hot melt glue and it was used to cold press for 24 hours. This procedure ensured that the glue would fully stick on the aluminium blocks and the test pieces. A tension load was applied perpendicular on the surface of each specimen at a uniformed rate of 2 mm/min until failure occurred. The main purpose of this test was to determine the interfacial bonding strength between fibres in the boards [15]. It was influenced by the factors including resin formulation, content, distribution, press schedule, and curing condition [28].

Figure 4 showed that there was slight difference in the IB value for both the UF and the PF sago particleboard. Sago particleboard with PF matrix showed increment in IB value by increasing the weight fraction of matrix until 15 wt% of PF content. The IB value increased due to the matrix that held the fibre firmly and increased the interfacial bonding between the particles in the particleboard [12]. The higher amount of resin had enhanced stronger interfacial bonding between particles in the boards, thus prolonging the ability of the boards to withstand the pulling force during the test [15]. The wetting properties from PF matrix caused it to easily penetrate into the particles and created better mechanical interlock. At the same time, the matrix would fill up the voids and created better bonding between each particle. Another possible explanation for the superior performance of PF at 10 wt% and 15 wt% was related to its high mobility on sago

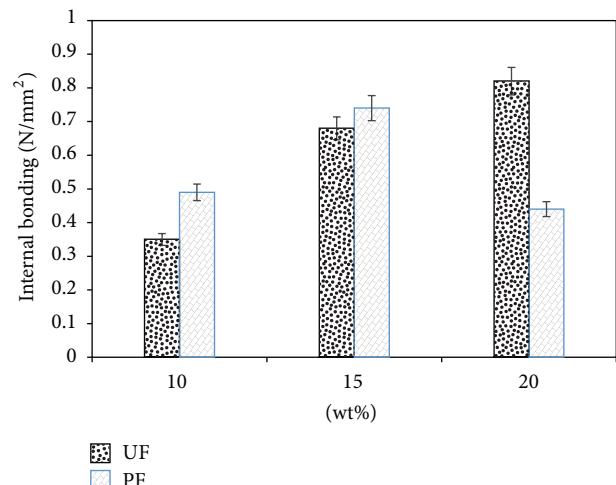


FIGURE 4: Internal bonding of sago particleboard versus resin matrix content (wt%).

particles [29]. When the PF droplets are placed on the sago particles, they spread out spontaneously without the need of any external forces. The high mobility of PF had caused the matrix to penetrate deep into compressed particles and repair the weak zones in the particleboard (usually damaged by cracks and tissues) by sticking them together.

20 wt% of UF sago particleboard showed the highest internal bonding because there was sufficient resin to wet all the sago particles in the composite specimens. The NH_4Cl that acted as catalyst in UF had increased the bonding strength compared with the PF with no catalyst applied [30].

Sago particleboard with 10 wt% and 15 wt% of UF matrix lowers the IB value compared with the PF sago particleboard with the same amount of matrix to be used. This was due to the insufficient UF for the particle bonding and, thus, affected the wetting properties. High viscosity of UF caused slow resin diffusion in sago lumen and decreased in mechanical interlocking [24]. This reduced the mobility of polymer hydroxyl group and caused the unstable methyl ether bridge not to change to methylene bridge; consequently the bonding strength became weak [24]. The internal bonding strength of UF-bonded particleboards depends largely on the strength of adhesive and its bonding to particles. It had great influence on the degree of hydrogen bonding between molecules and condensation reactions between the methylol and amide group [31].

Sago particleboard with 20 wt% of PF content did not show better IB performance because PF had lower flow rate with low solid content (41%) on the physical properties and required higher temperature and longer pressing time to cure the core mattress. This is to improve the plasticization of sago particles and bonding quality [29]. Excessive PF matrix did not improve the IB because the matrix would evaporate during the hot press and did not bond well with the particles. Hence, this had reduced the glue bond formation at the core mattress [29]. The higher water molecules in core mattress had reduced the internal bonding strength.

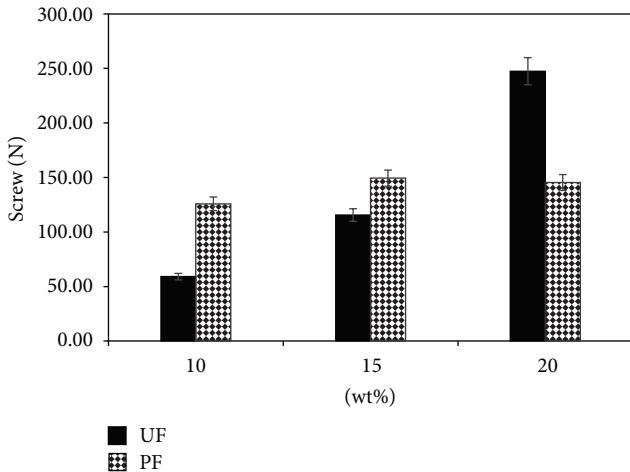


FIGURE 5: Screw test of sago particleboard versus resin matrix content (wt%).

3.2. Screw Test. Figure 5 illustrates the screw test of different types of matrix applied to the sago particleboard. The results showed that UF had shown the highest screw test at 20 wt% of matrix.

The screw test value increased when the UF matrix increased up to 20 wt%. The UF matrix bonded well with the particles and reduced the existence of voids. Hence, this had improved the ability of boards to hold the screw begging pull-out [15]. The efficiency of interfacial bonding between particles indirectly increased the ability of boards to hold the screw begging pull-out, and hence the screw test value increased [15]. Particleboard filled with higher dosage of UF resin caused the matrix to flow across surface, transfer to substrate, and penetrate into the cell wall. When the screw was embedded tightly into the particleboard, it was difficult to be extracted during the test.

The PF matrix only bonded well at higher weight fraction of particles. This was because the low viscosity of PF allowed it to flow easily through the sago particles and it managed to bond well between the particles. By increasing the dosage of PF into the sago particleboard, the embedded strength would not improve because the PF matrix flowed over or evaporated during the fabrication process.

The UF matrix interacted with sago specimens better than the PF matrix. Sago particles have hydroxyl groups in their three main components like cellulose, hemicellulose, and lignin while the UF matrix could react with hydroxyl groups better than the PF matrix. PF did not show better screw test results because the sago particle would absorb water and lose some of its strength when it was wet. Hence, the PF matrix had weakened hydrogen bonds with the sago particles and created the failure zone [32].

3.2.1. Tensile Strength. Figure 6 showed that the tensile strength had great influence on UF and PF matrix and they were strongly dependent on the bonding strength between the polymer matrix and sago and surface topology and lignocellulosic of sago particles [10]. Figure 5 showed that UF

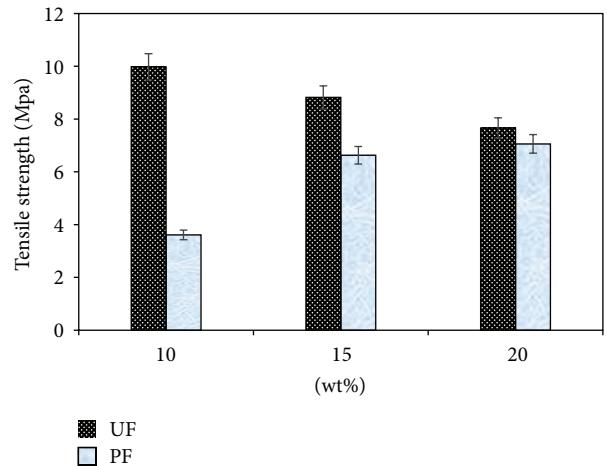


FIGURE 6: Tensile strength of sago particleboard versus resin matrix content (wt%).

had better bonding between polymer matrix and sago. This was due to the good wetting of the sago particles by the UF matrix that formed of a chemical bond between particles and matrix [10].

The UF particleboard exhibited better tensile strength than the PF particleboard. This could be attributed to the strong binding force and compaction strength of UF resin at the resin-sago interface. The high tendency of the resin penetration into the pores and crevices of the sago besides the three-dimensional bonding effect resulted in better mechanical interlocking and increased the efficiency of stress transfer along the interface [5].

Particleboard with 10 wt% of PF showed the lowest tensile strength. This was due to inefficient stress transfer at the particle/matrix interface and had created the debonding between the particle and matrix [17]. The viscous resin could not allow the matrix to penetrate into the pores and crevices of the sago, and hence the tensile strength reduced [5].

The tensile strength increased with the PF loading. This was because PF had better interfacial adhesion and improved strength of lignocellulosic materials [33]. On the other hand, UF decreased the tensile strength when the matrix loading increased. This was because the incorporation of cellulosic or lignocellulosic filler with UF matrix might not increase the tensile strength of the composite material [23]. The interfacial interaction of sago and UF matrix introduced a new interfacial region that affected the stress transfer in the sample. During the tensile test, the plasticizer molecules might allow the macromolecular chains to undergo stretching and slippage.

3.2.2. Impact Strength. Figure 7 represents the impact properties of UF or PF sago particleboard. The result showed that UF had better impact strength than PF. This was because UF has better fibre-matrix bonding compared with PF [33]. UF had better interfacial interaction between the fibre and matrix. Hence, this reduced the pores in the UF sago particleboard and enhanced the impact properties. This showed that UF

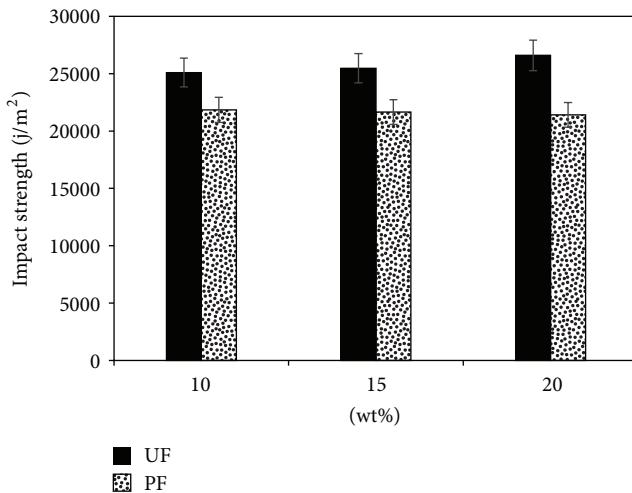


FIGURE 7: Impact strength of sago particleboard versus resin matrix content (wt%).

penetrated well into the sago particles and caused the material better resistance to withstand fracture when undergoing stress at high speed.

UF showed different impact strength properties compared with PF. The increment of UF loading into the particleboard strengthened the particleboard. UF did not show high impact strength at 90 wt% sago loading. This was due to the poor dispersion of particles in the matrix which led to weak stress transfer from matrix to particles when load was applied [34]. High fibres loading caused difficulties for matrix in flowing through and led to weak stress transfer from the matrix to the fibres [31]. According to Dungani et al. (2014), the impact failure of the composite might be caused by matrix fracture, fibre/matrix bonding, and fibre pull-out [33].

PF showed the decreasing impact strength due to the resin loading. At 10 wt% loading of PF, it showed the highest value of impact strength due to the high interfacial interaction between the fibre and matrix. This caused the greatest impregnation of resin PF within the pits or pores in the particleboard and enhanced the impact properties [11]. The higher resin loading of PF did not promote better impact strength because it would impart brittleness to the composite material and caused the material not to be able to resist the fracture under the stress applied with high speed efficiently. Besides, there were disruptions in the homogeneity of matrices such as a tendency to form agglomerates and this caused the loads not to transmit effectively between particles. Moreover, low loading levels of fibre at 80 wt% fibre + 20 wt% PF matrix had higher degree of critical defects to the composite structure with voids and poor bonded interface region [35]. Such defects had reduced the impact strength.

PF matrix with higher loading of fibre had better impact strength. This was because higher loading of fibre could reinforce cellulose, counterbalances the defects, and improved the toughness [35]. On the other hand, PF at higher loading of fibre repaired the weak boundary between the particles and increased the ability of absorption energy.

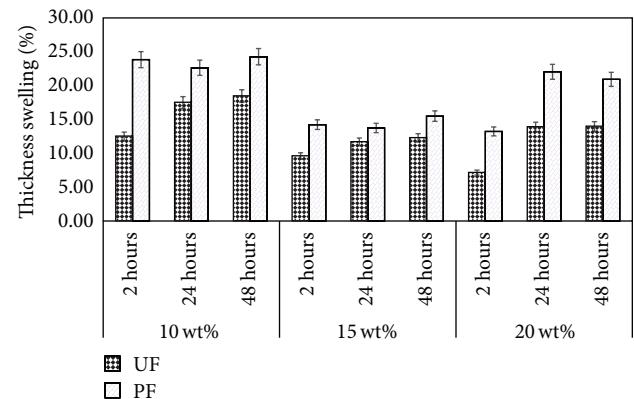


FIGURE 8: Thickness swelling of sago particleboard versus resin matrix content (wt%).

Besides, the stress transfer in the sago particleboard depended on the physical and chemical bonding of the matrix and fibres [33]. Factors such as nature of the constituent materials, fibre-matrix interface, and construction and geometry of particles highly influenced the impact properties [36]. Low impact strength could be due to the presence of many preexisting micro compressive defects along the fibres [35]. These defects would form small kinks in the microfibrillar structure and the presence of crystalline regions in the cell wall [35].

3.3. Physical Test

3.3.1. Thickness Swelling (TS). Figure 8 shows the effect of UF and PF resin on thickness swelling. It was observed that, by increasing resin loading in both particleboards, resistance against water being absorbed was developed. The swelling percentage of particleboard was slightly reduced after being impregnated with higher loading of UF or PF resin and led to better dimensional stability. Both resins reduced the porosity and minimized the dimensional changes.

Natural fibre-based polymer composites had poor water resistance due to the presence of polar groups, which would attract water molecules through hydrogen bonding [37]. This phenomenon led moisture to build up in cell walls and at the fibre/matrix interface. The polar hydroxyl groups in sago form hydrogen bonds with water molecules. This had been attributed to the water being absorbed through the formation of hydrogen bonds which increased with weight fraction and parenchyma tissue [38]. The presence of OH groups enhanced the water absorption by forming hydrogen bonding with water molecules that caused the particleboard dimensional changes.

UF sago particleboard had better dimensional stability than PF sago particleboard. This could be attributed to the strong UF resin properties with stable adhesive forces [3]. Hence, UF resin provided better water resistance than the PF resin. Besides, UF had better resistance against the water due to the sufficient bonding strength with reduction in internal force generated by water [37, 38].

PF sago composite had shown poorer thickness swelling properties compared to the UF. This was because PF resin contained a higher amount of water and low viscosity and low solid content compared with UF. PF needed higher temperature or longer time for the hot press process due to the PF properties which was more liquid. During the hot press process, the moisture in PF evaporated more slowly compared to UF and caused the PF located in the parenchyma cells. Hence, poor bonding between the particles had caused the dimensional stability to be reduced [38]. TS of composite panel was influenced by the quality and distribution of adhesive, moisture content, compatibility, and chemical composition of furnish [24].

Sago particleboard with PF 15 wt%, UF with 15 wt%, and UF 20 wt% had met the minimum TS requirement of JIS A 5908 Standard by not exceeding 16% of thickness swelling. Although the standard for JIS A 5908 only required doing the test until 24 hours. The sago particleboard underwent 48 hours of test to obtain better understanding of thickness swelling behaviour for outdoor application. Based on the result, all the sago particleboard continued increasing in thickness swelling. However, it would slow down after 24 hours and reached saturation after 48 hours with stable dimensions.

3.3.2. Water Absorption (WA). Figure 9 showed that both composites had the same pattern of water uptake where most of the water was absorbed speedily in the first 2 hours. Higher initial water absorption rate might be due to diffusion phenomenon as fluid spreads through the capillaries, vessels, and cellular walls of sago. Capillaries and cavities on the surface are filled up by water instantaneously, hence water concentration on the surface saturated rapidly, and moisture movement was restricted to the inner of composites. Water moved easily into large cavities instead of in small cavities due to the presence of air bubbles trapped inside small cavities [39].

The result illustrated the water absorption of UF and PF particleboards with different fibre content. It could be clearly seen that water absorbed increased with the fibre content. The highest water uptake was found in low loading 10 wt% of matrix in particleboard for both UF and PF. This was due to the presence of more hydroxyl groups in the parenchyma tissue that enabled more hydrogen bonding to be formed and the parenchyma behaved like a sponge with which it was easier to absorb water [11, 38]. There was more surface area on sago particles and parenchyma tissues to absorb moisture [4, 38].

On the other hand, the porous structure of sago particleboard had led to large initial uptake. The presence of free hydroxyl group and other polar groups in sago results in poor compatibility between the fibre and matrix. Hence, this caused the sago particleboard to take up a high amount of water which is trapped into the interfibrillar space of cellulosic structure and micro voids [37]. When the specimens were immersed in the water for longer time, the water molecules would enter into the particleboard through the voids and be absorbed by the polar OH groups of

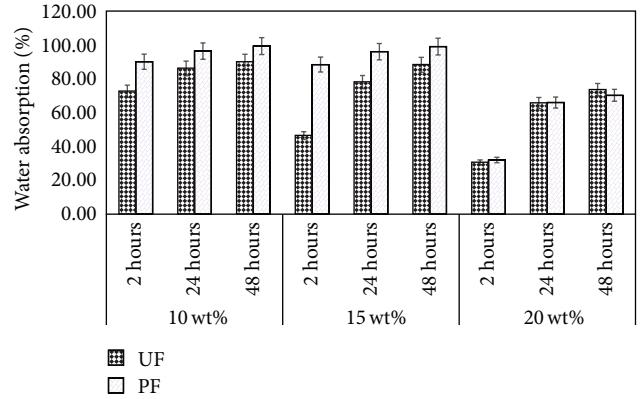


FIGURE 9: Water absorption of sago particleboard versus resin matrix content (wt%).

sago particles and caused interfacial debonding at the same time.

Besides, the hydrophilic nature and high porosity of sago content enhanced the water diffusion process and took a longer time to achieve saturation [4, 34]. The same was observed by other researchers; the water uptake capacity of the particleboard decreased with the increment of resin loading. Both matrixes UF and PF showed that the water absorption decreased with increasing of resin content. This might be due to the chemical components in the resin that cross-link with hydroxyl groups of the sago and hence reduced the hygroscopicity of the boards. Hygroscopic expansion was affected by monomer, polymerization rate, cross-linking and pore size of polymer network, the bond strength, interaction between polymer and water, and filler resin interface [15].

UF had better water resistance compared with the PF because the cohesive and binding force of UF resin were stronger and more sustainable [6, 37]. The reason for less water absorption of particleboard with UF resin loading as compared to PF resin loading is due to better interfacial contact between fibre-matrix bonding in UF [38]. UF matrix had better bonding properties to cover the parenchyma tissues from absorbing the water. By increasing the resin loading in the UF particleboard, the void spaces in the parenchyma were reduced and penetrated into the cell wall of sago. The presence of urea in UF increased the molecular weight of resin system and thus limited the penetration into the cell wall of the sago and filled up the lumen which formed an internal coating and reduced the water absorption [22].

The results showed that sago impregnated with higher loading of PF reduced the degree of water absorption. This reflected the replacement of hydroxyl group with carbon atoms in the PF chains [11]. The molecular weight distribution of resin significantly influenced the viscosity and the ability of resin to penetrate the cell wall [22]. PF has higher amount of water as compared to UF. This caused the moisture in PF to need a longer curing time to achieve curing. Incomplete polymerization of matrix might occur in the lumen making the solid content of PF located fully in the parenchyma cells thus leaving more air spaces for moisture uptake [22, 38].

TABLE 4: Results for sago particleboard with different matrix analysis by TGA.

Matrix	Temperature range (°C)	Temperature peak (°C)	Weight loss (%)	Residues (%)
PF	53.10–166.73	69.58	4.89	34.66
	170.44–594.93	295.39	60.45	
UF	53.48–158.67	80.40	4.25	19.92
	174.46–544.40	311.04	75.83	

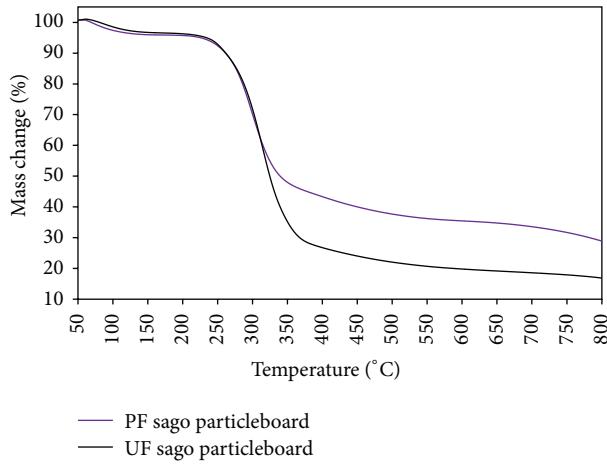


FIGURE 10: TGA of PF and UF sago particleboard.

All the UF/PF sago particleboards were not applicable in the industry use due to the requirement that they should be less than 60%. The particleboard might improve by adding some wax for water resistance or laminated with PVC sheet.

3.4. Thermal Properties

3.4.1. TGA of Sago Composite. The thermal behaviour of sago particleboard with different matrix was determined. Figure 10 and Table 4 showed the details of the decomposition of the sago particles. PF particleboard showed the highest weight loss at the beginning compared to UF particleboard because of its fixed moisture. Since PF sago particleboard had lower percentage of the solid content from the original, it took longer time than UF sago particleboard to remove the moisture. PF sago particleboard involved the evaporation of water and had high volatility at around 53.5°C–166.7°C, while the water evaporated from the UF sago particleboard at around 53.5°C–158.7°C.

The second step of the PF sago particleboard decomposition was produced at peak temperature of 295.4°C within the temperature range of 170.4°C to 594.9°C, with 60.45% of weight loss. The pyrolysis of sago as well as PF components was completed at about 595°C. It was believed that the pyrolysis residue of sago particles and PF decomposed slowly until the end of the process [40]. PF sago particleboard corresponds to degradation, where sago degraded to hemicellulose, cellulose, and lignin while PF degraded to carbon, hydrogen, and oxygen. The second peak temperature in this study at 295.4°C was attributed to the cross-links that were formed and small exposed groups of the cured resin

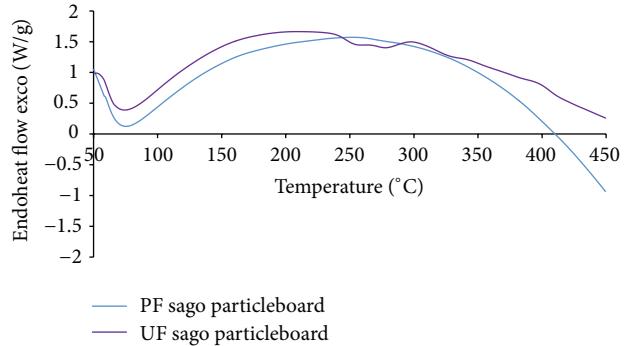


FIGURE 11: Sago particleboard with different matrix analysis by DSC.

were removed. According to the research, the condensation reactions between functional groups of the cured PF adhesive could cause additional cross-links. The condensation reaction was between phenol and methylene group to form a carbon-hydrogen cross-link. The methylene bridges were decomposed or broken into methyl groups with the formation of both phenols and cresols [41].

For UF sago particleboard, levoglucosan is the main constituent of decomposed products besides water, urea, and formaldehyde [42]. The thermal degradation would begin at around 174.5°C to 544.4°C, right after the materials had absorbed certain amounts of heat energy. The heat initiated the degradation process which broke down the structure and caused the molecular chain ruptures [42]. For the UF, the most probable phases formed during the second step of decomposition are water, carbon dioxide, and carbon [43]. The results of the recent research showed that PF had better thermal stability due to the characteristic structure of layers in a polymer matrix and their shape and dimensions that were close to molecular level as well as the changed thermal properties [44].

PF sago particleboard had higher percentage of residue as compared with UF sago particleboard. The residues of PF and UF sago particleboard were 34.66% and 19.92%, respectively. PF adhesive was slightly more resistant to extreme temperature at 800°C [41]. The highest weight loss temperature of PF and UF sago particleboard was 295.40°C and 311°C in which UF was lower than PF by 15.7°C.

PF sago particleboard had higher thermal stability than UF sago particleboard. This was related to high crystallinity index that possesses high thermal stability [4]. PF sago particleboard took longer heating time and higher temperature to increase the decomposition without changing the structure or losing strength [45].

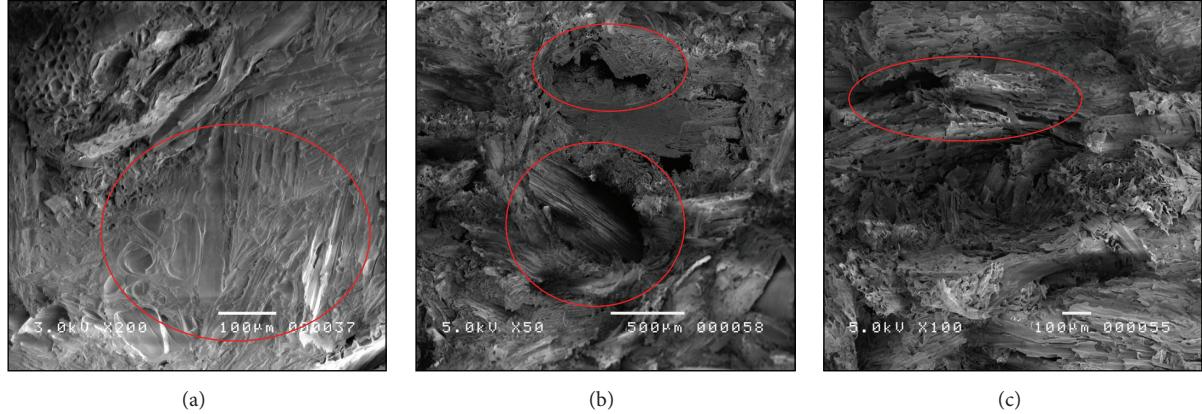


FIGURE 12: UF sago particleboard. (a) Particle bond with the UF matrix (b). (c) Boundary of the particles/void/debonding.

3.4.2. DSC of Sago Composite. Figure 11 shows the DSC thermogram of sago particleboard with different matrix. Particleboard with PF matrix had the highest melting temperature of 75.5°C compared to particleboard with UF matrix that was only 73.3°C. The particleboard manufactured with PF matrix had a higher melting temperature due to the cross-linking reaction with epichlorohydrin that occurred in sago particles [46]. This led to better interaction between sago particles with the PF matrix. Thus, more heat was needed to complete the melting process.

The temperature for curing and conversion rate of curing began with similar trend. UF had higher curing characteristics peak, thus giving rise to a wide exothermic peak [2]. Research had found that UF required a low curing temperature and short press time. PF required a higher curing temperature and long pressing time [47].

Particleboard made by UF matrix showed multixothermic peaks and these could be due to the methylation and condensation reaction [41]. Methylation is a nucleophilic which involved the addition of formaldehyde to urea ring while the condensation was the cross-link (cure) reaction by methylolated urea into polymer molecules.

PF matrix had the highest viscosity compared to UF and was difficult to achieve an efficient distribution in the particleboard. According to Atta-Obeng, PF with higher viscosities could be warmed at 40°C to give acceptable spraying properties on particles [41].

During the manufacturing process, the phase change for the PF matrix from homogenous to heterogeneous occurred when it was mixed with cellulose from sago particles. The cellulose from the sago particles would change the PF matrix from a continuous phase to a dispersive one. In a homogenous PF curing system, the PF molecules formed a large cross-linked network. However, it was possible that the addition of cellulose to PF system resulted in barrier to the PF cure. This caused the PF oligomers molecules to have unrestricted space to polymerize completely and achieve the maximum reaction enthalpy. With addition of cellulose, the polymerization might be restricted by the distance between cellulose polymers resulting in lower reaction enthalpy and maximum curing temperature [41].

3.5. Morphological Study. The morphological analysis of tensile fracture surface of sago/UF particleboard was shown in Figure 12. The particles were well-embedded with the UF matrix, although there was some debonding between the particles in the particleboard. The debonding had indicated that there was no bonding between the particles and matrix and created the voids between the particles [48]. Improper bonding could be due to the surface roughness from the incompatible blend of different size of the particles. The immiscibility of the particles caused the weak interfacial adhesion and starch granules tend to agglomerate and resulted in low strength.

4. Conclusion

In this study, it was clear that sago particleboards with different matrix and weight fraction had an impact on the mechanical, physical, and thermal performances. The boards' strength was enhanced when the resin loading increased, but this was only applicable to certain percentage of resin loading and, after the optimum, the strength would drop. From the TGA/DSC study, it could be concluded that sample with PF sago particleboard had better thermal stability and denser in structure while the UF sago particleboard had better curing properties. The results showed that the resin content had significant effects on the water adsorption and thickness swelling expansion. PF sago particleboards with 15 wt% met the M-1 specification, both the PF and UF sago particleboard with 20 wt% met the M-S standard of American National Standard A208.1-2009 for wood particleboards and fulfilled the commercial purpose. Only the UF sago particleboard with 10 wt% and 15 wt% met the M-2 specification for industrial purpose. The main advantage of sago UF/PF particleboard over solid wood or plywood was that its cost was very low. Compared to plywood furniture of similar dimensions, particleboard furniture costed less than half. The particleboards were manufactured to the desired dimensions, and thus standard pieces of furniture could be mass-produced using these boards. This further brings down the costs due to no carpenter work involved and ready-to-buy products for customers with zero waiting

time. Particleboards were very light in weight and hence the furniture made from these boards was easy to transport and move around. However, particleboard was not strong in its mechanical properties compared with plywood but it still meets the minimum requirement for furniture industries application. This study showed that sago particles could be utilized as a raw material in particleboard manufacturing. The findings showed that the new application for sago might potentially reduce the pressure on the forest resources as well as providing additional income to the farmer in Mukah, Sarawak.

Competing Interests

The authors declare that they have no competing interests.

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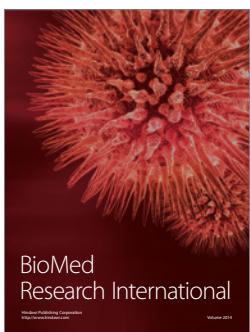
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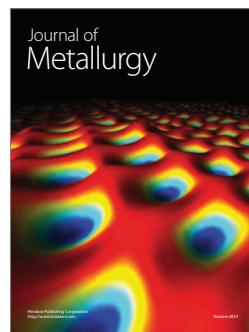
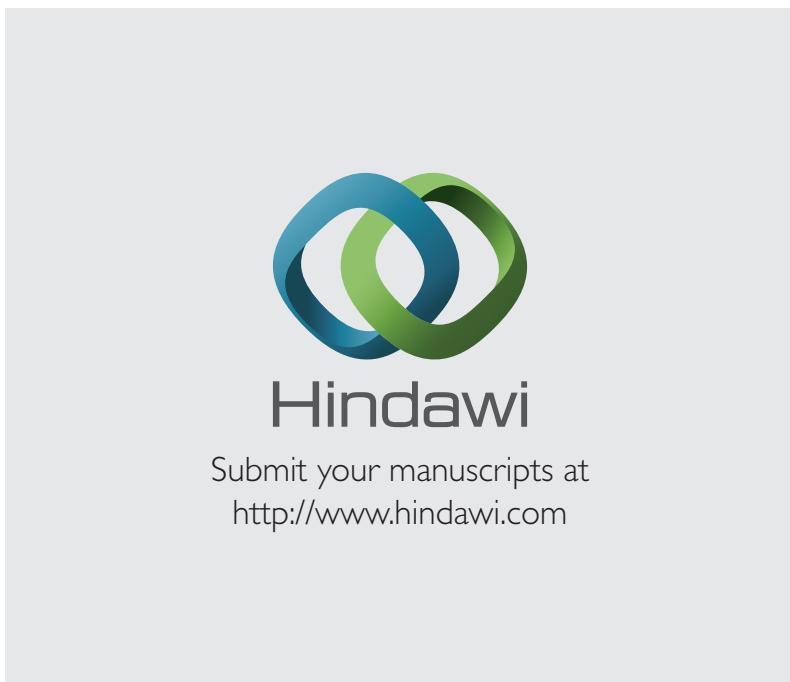
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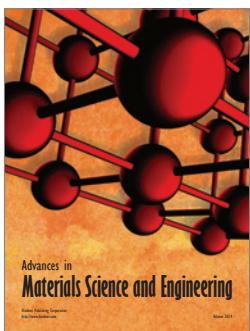
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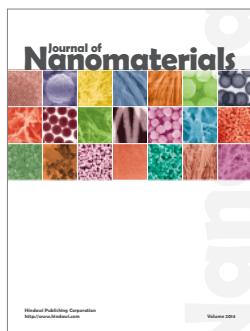
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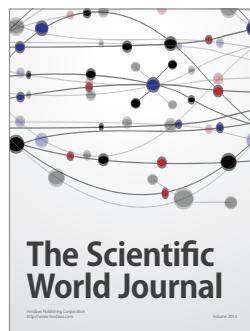
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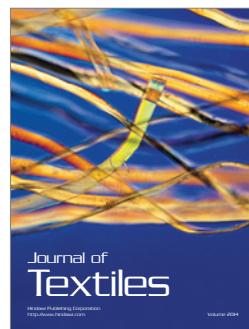
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