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Review Article

Effect of Additives on Wood Pellet Physical and Thermal Characteristics: A Review

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Additives play a major role in wood pellet characteristics and are a subject of major interest as they act as binding agents for the biomass raw material. Past research has reported the use of lignosulphonate, dolomite, starches, potato flour and peel, and some motor and vegetable oils as additives for wood pellet production. This paper reviews the available research on the effect of different additives on wood pellets' physical and thermal characteristics. It was found that lignosulphonate and starch additives improve the mechanical durability but tend to reduce the calorific value of the wood pellets. Motor and vegetable oil additives increase the calorific value minimally but significantly increase carbon monoxide emissions. Corn starch and dolomite additives also significantly increase carbon monoxide emissions. In order to produce wood pellets with desired physical and thermal characteristics, a suitable additive with the right biomass material should be used.

1. Introduction

The Canadian government is promoting clean energy usage; accordingly, the provincial governments have chalked out plans to become completely coal-free in the near future [1]. However, according to the International Energy Agency, in 2009, wood energy that is considered clean comprised only 4% of Canada's total primary energy supplies [2]. Wood pellets have emerged as a very successful renewable fuel source for energy production, due mainly to their many beneficial characteristics, including high density and calorific value, low moisture content, and relative convenience of transportation and storage. Wood pellets are wood fuel made from compacted sawdust and other wood waste [3]. Residential use of the prime class wood pellets have 6 ± 1 mm diameter and 3.15–40 mm length (EU standards) [4], and 5.84–7.25 mm diameter and 3.81 ± 0.0381 mm length (USA Standards) [5].

Canada is emerging as one of the world leaders in wood pellet production. The wood pellet production capacity in Canada has grown from 300,000 tonnes in 1997 to 2.93 million tonnes in 2011 [6, 7]. This growth is due in part to the European Union's (EU) renewable energy promotion policy, as 90% of total Canadian pellet production goes overseas while domestic usage is extremely low [8]. Price of wood pellets in Europe ranges from US$215 to US$275 per tonne, whereas in the North American market, the average domestic residential retail price ranges from US$175 to US$250 per tonne [9]. Wood pellet production plants are present in almost all provinces of Canada, but the majority of pellet production comes from Western Canada (British Columbia and Alberta).

The quality of wood pellets is determined by a few key parameters including moisture content (MC), calorific value, amount of fines, mechanical durability, particle density, ash content, and ash melting point. These parameter values are defined in the prEn 14961-1 (EU) and PFI (United States of America) standards. The values of these physical and thermal parameters are affected by using different binding agents or additives in wood pellet production. According to the EU standards, additives that improve fuel quality, decrease emissions, or boost burning efficiency can make up to a maximum of 2% of the total mass of the wood pellets [10]. The most commonly used additives are lignosulphonate, starch, dolomite, corn or potato flour, and some vegetable oils [4]. These binding agents or additives also affect the production economics of the final product.

Lignosulphonate is a water-soluble anionic polyelectrolyte polymer, which is obtained as a by-product of the wood sulfite pulping process [11]. Lignosulphonates are used in animal feeds and have been considered as the most effective and popular binding agents for wood pellets. Normally 1% to 3% of lignosulphonates are used for effective binding of wood pellets [12]. Starch is formed from two polymers, amylose, a linear polysaccharide, and amylopectin, a large highly branched polysaccharide, and is obtained in various shapes and granular sizes when cereals or tubes are separated into protein and fiber components [13]. The shapes and granular sizes of the starch affect its distribution in the wood material and consequently affect the pellet abrasion. Other additives, like vegetable oil or dolomite, are added for better lubrication during the pelletizing process [14, 15]. Binding agents are usually added to the production process either just before the core matrix pressing phase in the pilot-scale pelletizing machine [16], or as a continuous flow of raw material on a collector screw before the mixer buffer silo [17].

The binding agents also affect power consumption and usage of water during the wood pellet manufacturing process. Maize starch and lignosulphonate have been found to be better additives for power consumption per unit of wood pellet output as compared to the other additives [17, 18]. With no additives, the specific energy consumption for poplar wood pellet production was found to be 138 kWh per dry tonne [18]. The specific energy consumption value significantly decreased to 79 kWh per dry tonne by adding 2.5% maize starch, to 128 kWh per dry tonne by adding 2.5% lignosulphonate, and to 106 kWh per dry tonne by adding 5% lignosulphonate [18]. The lower specific energy consumption of using starch as an additive is due to the lubricating ability of starch. Water is added to the raw material before the pelletization process in order to obtain optimum moisture content. The use of additives affects the amount of water required in the wood pellet production process. For example, the use of dolomite as an additive increases water consumption significantly, whereas wheat starch does not have much effect on water usage [15].

Therefore, the past research shows that the additives and binding agents affect all the major characteristics of the wood pellets. The purpose of this study is to summarize the experimental data related to the effects of additives and binding agents on physical and thermal wood pellet characteristics. This literature review helps in identifying the need for further research in finding mixtures of additives and different raw materials for producing wood pellets having best physical and thermal characteristics, so that wood pellets remain competitive as a renewable energy option.

2. Physical Characteristics

The physical characteristics reviewed in this study include (i) moisture content, (ii) particle density and mechanical durability, and (iii) bulk density and pellet size.

2.1. Moisture Content. MC is expressed as a percentage of the original sample mass, and it has a strong influence on other wood pellet parameters, such as heating value, combustion efficiency, pellet durability, and bulk density. Different additives require different amounts of MC in the raw material in order to bind the material effectively. The use of starch as a binding agent requires MC for the raw material between 12.5% and 13.0%, whereas lignosulphonate requires MC values between 9.0% and 10.5% for the pelletization process [18]. When additives are used for making wood pellets, these decrease the final MC of the wood pellet. For example, wood pellets made of standard raw material (with 9.3% MC) and 1% or 2% lignosulphonate (with 8% MC) mixture result in a final pellet MC of 5.9% [17]. However, when the lignosulphonate dosage is increased to 2.5%, 5%, and 7%, it does not display a significant effect on the final MC of the wood pellet [18]. In case 5% potato peel residue (with 77.8% MC) and dry raw material (with 3.3% MC) are mixed together, the resulting wood pellets have 2.9% MC [17]. The use of starch significantly reduces the final wood pellet MC. Stahl et al. [13] found that when the raw material (with 12.1% MC) was mixed with 1% wheat starch, and the same amount of oxidized corn starch, the final pellet MC is reduced to 7.6%. Increasing dosages of wheat and maize starch further reduces the pellet MC [13]. Interestingly, if lignosulphonate and maize starch are added at the same time (1% of lignosulphonate and 1%, 2%, 3%, or 4% of maize starch), the final wood pellets MC decreases only by 0.5% [18].

From the above-mentioned literature, it is clear that the addition of starch has a higher impact in reducing the final wood pellet MC as compared to lignosulphonate. However, too much starch will make the final product extremely dry. The final MC of the wood pellet is very important, as it affects not only the calorific value, but also durability and abrasion of the product. Li and Liu [19] reported that a good quality pellet has MC ranging between 6% and 12%. Wilson [20] found that the highest pellet durability index with red oak samples has MC of 10%. Other studies also found that wood pellets having MC ranging between 9% and 14% are most durable and resistant to abrasion [21, 22].

2.2. Particle Density and Mechanical Durability. Table 1 presents particle density and mechanical durability of poplar pellets with different additives and a specific pelletization surface area. Particle density is the ratio of the sample mass and its volume including pore volume [23]. Single pellet density is variable and depends on wood pellet machine packaging pressure and wood species. Extremely high density is not good for combustion efficiency, as the access to oxygen is prevented when the wood elements are very tightly packed, and that consequently degrades the burning process. These strength parameters are particularly important for storage and transportation of wood pellets over long distances, as it is important to minimize dust and fracture formation during storage and transportation. These parameters do not exist in the prEN 14961-2 and PFI standards [4, 5]. However, according to the German and Austrian standards, a single pellet density should be between 1000 and 1400 kg/m^3 [24].

Mechanical durability is defined as abrasion resistance and mechanical strength as compressive and impact resistance [25]. According to the European standards, high-class pellet mechanical durability should not be less than 97.5%, and according to the PFI standard, this parameter should

Table 1: Particle density and mechanical durability of poplar pellets using different additives, with specific pelletization surface area of 5.6 cm^2/kW [18].

Additive	MC (%)	Particle density (kg/m^3)	Mechanical durability (%)
LS 2.5%	9.9	960	98.0
MS 2.5%	9.9	970	95.9
LS 5%	8.5	1080	98.8
MS 5%	9.8	960	97.3
LS 7%	9.5	1060	98.4
MS 7%	9.0	1000	96.4
MS 0.95% + LS 1.05%	6.3	1070	93.2
MS 1.94% + LS 1.06%	8.4	1030	95.6
MS 2.94% + LS 1.06%	8.0	1100	97.1
MS 3.93% + LS 1.07%	7.2	1130	97.1

LS: lignosuphonate; MS: maize starch.

not be less than 96.5% [4, 5]. MC, particle size, and raw-material chemical composition affect wood pellet mechanical durability [20]. The mechanical durability of wood pellets is stable with MC values ranging between 9% and 14% [21], and the influence of abrasion disappears for MC values between 8% and 12% [19]. If the raw material MC is lower than 7%, pellets will not have the necessary strength characteristics, as there will not be enough moisture for lignin to form a strong bond with the pellet particles.

Mediavilla et al. [18] conducted a comparative study to analyze the impact of different additives (lignosulphonate, maize starch, and their different combinations) on the particle density and mechanical durability under similar initial conditions (same raw material, same dosage of additive, same MC, and same compression rate). The particle density varied between 960 kg/m^3 and 1130 kg/m^3, and the mechanical durability varied between 93.2% and 98.8% for different additives and their combinations. The addition of lignosulphonate resulted in higher mechanical durability as compared to the addition of maize starch.

Nosek et al. [26] further found that using additives (such as motor oil, corn starch, sodium carbonate, urea, vegetable oil, and dolomite) at a dosage of 0.5% decreased the wood pellet particle density. The strongest effect on decreasing the wood pellet particle density was found when corn starch and dolomite were used as an additive [26]. Using softwood as a raw material, Kofman [14] found that 1% and 2% addition of binding agents (lignosulphonate and potato flour) increased wood pellet's mechanical durability from approximately 96% to 98%. Addition of 1% of potato flour improved mechanical durability more than the addition of 1% of lignosulphonate; however, 2% dosage of either additive shows the same result [17]. Stahl et al. (2012) also found that the addition of starch additives increases wood pellet mechanical durability [13]. All types of starch (native wheat starch, oxidized corn starch, native potato starch, and oxidized potato starch) help in increasing mechanical durability as the starch dosage increases. Addition of 2.8% oxidized corn starch had the best overall effect among all the starches, with the mechanical durability index increasing from 93.6% (native wood) to 98.1%.

2.3. Bulk Density and Pellet Size. Bulk density is a parameter, which directly affects storage and transportation costs, as higher bulk density promotes product compactness in the shipping container. Bulk density depends on pellet size (both length and diameter), single pellet density, and moisture content. Pellet size further impacts the pellet strength, as a longer pellet can be easily broken as compared to a shorter one. The bulk density of 6 mm diameter pellets (with average particle density of 1764 kg/m^3) is found to be 609 kg/m^3, compared to the bulk density of 8 mm diameter pellets (with average particle density of 1687 kg/m^3), which is found to be 621 kg/m^3 [27]. Pellet size (length) also affects the burning efficiency. Sikanen and Vilppo (2012) found that wood pellet burning temperature decreases by 31% and flue gas temperature by 25%, as the pellet length increases from 5.8 mm to 13.1 mm [28]. The use of binding agents as additives has been found to have an effect on the pellet length. Stahl et al. (2012) found that starch additive significantly increases the wood pellet length when no cutting blade is used [13]. Raw materials with larger particle size and higher MC reduce bulk density of the product, while higher process temperatures and pressures increase the bulk density [12]. Tabil et al. (2011) and Samuelsseon et al. (2012) also found an inverse negative relationship between the moisture content and bulk density [21, 29]. The bulk density of softwood pellets increases by 20–25 kg/m^3 with an addition of 5% bark additives [30]. This is because bark contains 8–10 times higher concentrations of metals, such as aluminum, iron, and sodium than in stem wood. Other additives, such as lignosulphonate and different types of starch, decrease the moisture content of wood pellets, thereby increasing the bulk density of the product.

3. Thermal Characteristics

The thermal characteristics reviewed in this study include (i) heating value, (ii) ash content, ash melting point and elemental composition, and (iii) emissions formation.

3.1. Heating Value. Heating value (calorific value) is the most important wood pellet characteristic, as higher heating value means higher energy output from the same amount of product and consequently lower cost for the customer. Heating value is either expressed as low heating value (LHV) or high heating value (HHV). LHV determines the maximum amount of heat generated excluding the heat of vaporization, whereas HHV is the heat value produced by total combustion of the fuel unit. Calorific value (kilo Jules/gram) is related to the concentrations of carbon, hydrogen, oxygen, sulphur, nitrogen, and ash present in the wood pellet sample and is calculated using the following equation [31]:

$$\begin{aligned} \text{HHV} = {} & 0.3491\text{C} + 1.1783\text{H} - 0.1034\text{O} \\ & - 0.0211\text{A} + 0.1005\text{S} - 0.0151\text{N}, \end{aligned} \tag{1}$$

where C, H, O, A, S, and N represent the mass fractions of carbon, hydrogen, oxygen, ash, sulphur, and nitrogen, respectively. HHV is positively related to carbon, hydrogen, and sulphur concentration but negatively related to nitrogen and oxygen concentration. Therefore, if the biomass used for producing pellets is obtained from nitrogen-fixing species (e.g., alder trees), the calorific value of these wood pellets would be much lower. Wood bark is also known to contain more nitrogen than the wood [32, 33]. Softwoods in general have a higher heating value than hardwoods [34]. The average gross calorific value of wood is 20.25 MJ/kg [4]. The presence of lignin also increases the heating value of the woody biomass [35]. The heating value is also affected by the thermal conductivity, which depends on the heat conductance during pellet storage [36, 37]. The additives (lignosulphonate, potato flour, and potato peel residue) do not significantly impact the calorific value of the wood pellets [17]. However, 0.5% dosage of motor oil and vegetable oil increases calorific values, and 0.5% corn starch additive decreases calorific values by about 0.5 MJ/kg [26].

3.2. Ash Content, Ash Melting Point, and Elemental Composition. Ash content is the percentage by weight of ash present in the wood pellet in relation to the fuel weight. High ash content will decrease the stove efficiency, and the stove requires cleaning more often. According to the EU standard, premium class wood pellet ash content should be less than 0.7%, and PFI defines this parameter to be less than 1% [4, 5]. Kuokkanen et al. (2011) found that a supplement of 1% potato flour does not affect ash content, but 2% dosage of the same additive increases ash content from 0.5% (native wood) to 0.6%. The 0.5% and 3% addition of dolomite also increases the ash content as compared to the reference sample [15, 17]. When lignosulphonate is used at concentrations of 1% and 2%, wood pellet ash content increases from 0.5% (native wood) to 0.6% and 0.8%, respectively [17]. However, 0.5% additive of wheat starch significantly reduced ash formation by two times [15].

Ash melting point is affected by the chemical composition of the biomass used for making wood pellets. The concentrations of calcium and magnesium in the biomass increase, and the concentrations of potassium, and sodium in the biomass decrease the ash melting point of wood pellets [4, 38, 39]. Low ash melting point could result in ash related problems, like slagging and sediment formation in the combustion chamber [40, 41], requiring frequent service of the wood pellet stove. According to the EU standard, the ash melting point has to be higher than 1200°C [42]. High concentrations of chlorine, potassium and sodium also enhance the likelihood of corrosion of the inner components of the stove or boiler system.

Additives change the wood pellet element composition, thereby affecting ash melting point behavior. Lignosulphonate additive at 1% and 2% dosages increases sodium content from 0.03 g/kg (dry weight) in native wood to 0.1 g/kg and 0.12 g/kg, respectively, and increases calcium content from 0.63 g/kg (dry weight) in native wood to 1.13 g/kg and 1.5 g/kg, respectively. Sulphur content also increases 10 times and 20 times, respectively, with 1% and 2% addition of lignosulphonate supplement [17]. Sulphur causes a major problem due to sulphates build up on the combustor heat transfer surfaces [35]. Lignin sulphonation also causes an increase in SO_x emissions [43]. However, no significant change in the potassium content was noted by adding lignosulphonate [17]. Nosek et al. (2011) found that 0.5% dolomite additive significantly increases ash melting point from 1200°C (native pellets) to approximately 1500°C, while other additives did not show any significant effect on ash melting point. However, the ash melting point is significantly impacted by using bark additive [26]. 5% of bark additive increased the ash-melting point (1230°C) of pure wood (scots pine) pellets to 1567°C [30]. Bark also contains large concentrations of silicium (Si) for protection. Whereas the concentration of Si is about 150 mg/kg in wood stem, it is as high as 2,000 mg/kg in coniferous bark and 10,000 mg/kg in hardwood bark [44]. Si forms potassium silicates at high temperature, which reduces the combustion efficiency of wood pellets [45, 46].

3.3. Emissions Formation. Wood fuel is considered a renewable energy source and can help decrease the Earth's atmospheric CO_2 concentration levels, if it replaces fossil fuels for energy production [43, 47]. The greenhouse gas emissions during wood pellet production and combustion are much lower compared to burning fossil fuels [48, 49]. However, wood pellets cannot be considered as CO_2 neutral energy source [50]. The carbon emissions for wood pellets is higher than for wood chips because of the additional energy consumed in wood pellet production stages, like drying and pelletizing. The amount of CO_2 emission varies from 30 kg/MWh to 106 kg/MWh and depends on the biomass species used, its source and the method for drying and pelletization [47]. The use of additives in wood pellets has been found to further increase the greenhouse gas emissions. For example, lignosulphonate addition significantly increases sulphur content [14], resulting in increased SO_x emission [24, 51]. Although the addition of corn starch (0.3% and 0.5%) and dolomite (0.1%) decreases SO_x emissions from 6 mg/m^3 to 4 mg/m^3, these additives significantly increase carbon monoxide (CO) emissions [26]. Pellets with no additives emit around 250 mg/m^3 of CO emissions, whereas pellets with 0.3% corn starch additive emit around 550 mg/m^3 of CO, and with 0.5% of dolomite additive emit around 700 mg/m^3 of CO [26]. However, no significant influence on NO_x emissions has been found [26].

4. Conclusions

The purpose of this study was to summarize the current state of the literature related to the effects of additives and binding agents on wood pellet physical and thermal characteristics. The physical characteristics reviewed in this study include (i) moisture content, (ii) particle density and mechanical durability, and (iii) bulk density and pellet size; whereas the thermal characteristics reviewed include (i) heating value, (ii) ash content, ash melting point, and elemental composition, and (iii) emissions formation. The findings of this paper can be summarized as follows.

The additives act as a lubricant and increase the production rate and decrease the energy consumption per unit output of wood pellets. Starch additives reduce the final moisture content more than lignosulphonate additives. However, too much starch will make the final product extremely dry, which affects mechanical durability of the wood pellets. Lignosulphonate additives result in the best mechanical durability values for wood pellets but do not display high particle density. Additives, such as motor oil, corn starch, sodium carbonate, urea, vegetable oil, and dolomite decrease the wood pellet particle density. However, corn starch and dolomite additives are the most effective in reducing the wood pellet particle density. All types of starch (native wheat starch, oxidized corn starch, native potato starch, and oxidized potato starch) increased the mechanical durability of the wood pellets, with the best results for mechanical durability obtained by adding oxidized corn starch.

Lignosulphonate does not affect the calorific value of the wood pellets, but significantly increases sodium and sulphur content, and consequently increases SO_x emissions. Motor and vegetable oil additives increase the calorific value minimally and corn starch and dolomite additives reduce the calorific values of wood pellets. Wheat starch additive significantly reduces ash formation, but dolomite additive increases ash formation as well as ash melting point in the wood pellets combustion. Both corn starch and dolomite additives significantly increase carbon monoxide emissions. Therefore, each additive has results in unique physical and thermal characteristics when used with different biomass materials. Further research is required in identifying mixtures of additives and different raw materials for producing wood pellets having the desired physical and thermal characteristics, so that wood pellets remain competitive as a renewable energy option.

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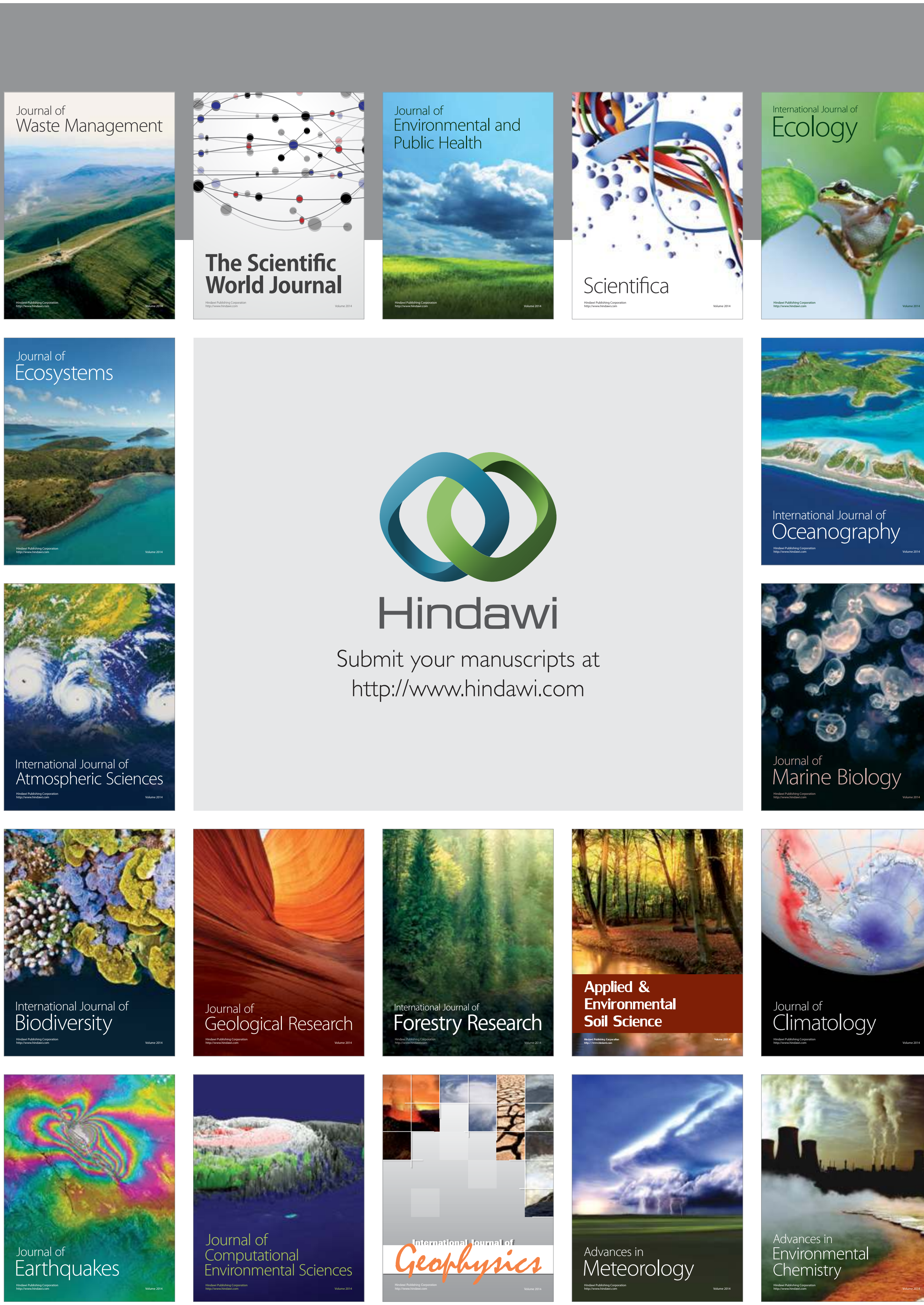

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