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A review on research has been made regarding recent developments aiming at reducing the negative environmental impact (because sometimes it might be positive) derived from industrial manufacturing processes of lignocellulosic-derived products, from their utilization, and also from their disposal at the end of their life. The most common journals of the wood science and environmental fields have been screened and relevant papers on this topic are referred and commented. This paper covers mainly lignocellulosic-based products taken as materials. That is saying, materials of common use and that were made incorporating mostly raw materials from forest or agriculture plants. Examples of such products are particleboard, waferboard, MDF, OSB, plywood and lignocellulosic-plastic composites. Excluded from this review are utilizations of biomass for heat/energy production or its processing for chemicals (e.g., ethanol). Important issues for this paper are: lignocellulosic wastes and sub-products recycling, Wood preservation environmental issues, VOC – Volatile Organic Compounds emissions, adhesion of wood and LCA – Life-Cycle Assessment of forest products.

Keywords Environmental impact; lignocellulosic-derived products; lignocellulosic waste

Introduction

Panels, mainly particleboard and MDF, have been manufactured with a wide range of lignocellulosic residues. Investigation with wheat and soybean straw for MDF (medium-density fiberboard) has shown that these raw materials make panels that are weaker, as compared to softwood fiber MDF, in mechanical and water resistance properties [1]. Nevertheless, some physical or chemical treatment of straw fibers has been recommended to overcome such drawback. A furnish made of virgin spruce-pine-fir fiber and de-inking paper sludge or primary sludge, having UF resin

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as binder, enabled to manufacture MDF that could meet the industrial standards [2]. Canola straw has been found suitable to make MDF, comparable to other fibers made of other non-wood plants [3].

Peanut hull, mixed up to 25% with European Black pine (*Pinus* nigra Arnold) chips, revealed to be suitable for general purpose particleboard manufacturing [4]. A conclusion of the same kind was reached with hazelnut shell flour bound with a mixture of UF (urea-formaldehyde) and MUF (melamine-urea-formaldehyde) resins, but in this case panels were of 100% hazelnut shell [5].

Timber of Jack pine (*Pinus banksiana* Lamb.) from dead trees, after prescribed burns and wildfires, could successfully be applied in the manufacture of OSB (oriented-strand board) [6], turning that raw material into an alternative for OSB commercial production. The addition of comminuted waste tire rubber to the furnish of OSB has had the effect of improving the moisture resistance of the panels, but the addition rate could only be up to 10% based on the oven-dry panel weight, to accomplish with the minimum property requirements stated by the relevant standards [7].

Wood-plastic composites have been the subject of extensive research and many products of the kind are now in the market. However, new raw materials have been tried. Wheat straw, cornstalk and corncob fibers have been investigated for HDPE (high-density polyethylene) composites [8]. Wheat straw filled HDPE exhibited superior mechanical properties compared to cornstalk, corncob and even wood flour filled HDPE. An LCA (Life-Cycle Assessment) of composite materials made of recycled thermoplastics (PP – polypropylene and HDPE) and biodegradable waste of little economic value, namely rice husks and recycled cotton, revealed that the composites have had a significantly reduced environmental impact compared to conventional virgin thermoplastics, mostly during the materials acquisition and processing phases [9]. The addition of micronized polyurethane powders obtained from flexible polyurethanes to UF and PF resins, to act as active extenders, has improved the performance of panels, namely plywood and particleboard [10]. Three major types of paper mill sludge, namely primary sludge (PS), secondary sludge (SS) and de-inking paper sludge (DPS) have been evaluated as adhesive fillers for PF (phenol-formaldehyde) resin [11]. The combination filler/resin PS/PF gave the higher dry and wet shear strengths of plywood.

Regarding the manufacture of cement, the addition of bagasse ash to cement mortars worked as an effective mineral admixture, with 20% as optimal replacement of cement [12]. In the field of wood-cement composites, fibers from mountain pine beetle infected wood of lodgepole pine (*Pinus contorta* var. latifolia Engelm.), even after 5 years tree death, gave good results in panel properties [13]. Thus, this beetle infected wood can be used as raw material for wood fiber-cement composites.

In the research area of composting of organic wastes, sawdust has been investigated as a bulking agent for sludge composting, either aerobic or anaerobic sludge [14].

In order to recycle and add value to agricultural residues, activated carbon briquettes have been manufactured with a mixture of eucalypt wood and rice husk from Uruguay, with concentrated grape must as a binder [15].

The residues of wood-processing companies in Germany and Brazil, namely wood and ash/charcoal residues, have been investigated for their potential as products for soil amelioration [16]. Such materials first adsorb a high amount of ions of N (nitrogen), P (phosphorus) and K (potassium), in a treatment phase; then, in the application phase, ions are slowly released in soil.

In order to make use of fire-killed trees for fuel, the effect of time that a fire-killed stands dead has on the fuel value has been assessed with ponderosa pine (*Pinus ponderosa* Douglas ex Lawson et C. Lawson) [17]. There was no difference in the heating value between living trees and killed trees even since about 10 years. Furniture wood wastes have also been assessed for fuel [18].

As a way of disposal and to contribute to maintain a good balance of nutrients in forest soil, ashes from the combustion of clean wood fuel may be returned back into the forest. With this aiming, Mellbo *et al.* [19]. performed a series of tests on elemental analysis and leaching of elements, these latter by applying three different methods.

Wood Preservation Issues

Nowadays, the main trends of research in the field of wood preservation/protection are divided in two: assessment of the environmental impact of traditional preservatives; and, development of new formulations with lower negative environmental impact and that are accepted by the public. Many new wood preservative formulations are based on natural and renewable products, mainly plant extracts, in order to mimic the systems Nature developed to protect plant tissues against the attack by fungi or insects.

Many treatment processes and chemicals make treated wood a toxic waste at the end of its utilization life, that needs to be disposed off by some controlled ways. One such group of chemicals that impart a very good biodeterioration resistance is CCA (chromium-copper-arsenic). Because it is very efficient it was used worldwide. Because of the toxicity of the treating solutions and because of concerns of environmental impact of wood in service, i.e., the possibility of leaching of constituting elements into soil, this group of formulations is now banned in many countries. But, because wood lasts for much longer in service when preserved, often lasts more than 40 years, even the countries where CCA was banned have a lot of treated wood that needs disposal, and the impact on the environment and human health of treated wood still in service is questioned.

Creosote treated-wood has been demonstrated to be a hazardous waste, as the concentrations of PAH (polycyclic aromatic hydrocarbons) in wooden crossties have been found to significantly exceed the critical limit that defines hazardous waste within the European Union [20].

The effect of wood species on the fixation rate of CCA-preservative has been assessed with sapwood of three wood species: trembling aspen (*Populus tremuloides* Michx.), red pine (*Pinus resinosa* Sol ex Aiton.), and red maple (*Acer rubrum* L.) [21]. The fixation of chromium, copper, and arsenic differed considerably among the wood species and was affected by treatment retention, resulting in differences in subsequent leaching of the chemicals.

The distribution of chromium, copper and arsenic in soils around CCA-treated wood structures has been determined [22]. The concentrations of those elements in soil were respectively 79.0, 98.9, and 128 mg/kg, compared to background levels of 48.2, 26.9, and 6.27 mg/kg. Arsenic (As) was more mobile in soil than chromium or copper. After analyses of arsenic in soil of three playgrounds near Melbourne, Australia [23], the highest reading was below 30 mg/kg. An average of this magnitude is used by APVMA to determine the level of risk, or lack of risk that might be posed to children playing on CCA-treated timber structures in Australia.

Moreover, the exposure to As by children playing on CCA-treated structures as been estimated using handloading data [24].

As an indication of leaching of arsenic into soil and of its mobility, arsenic (As) has been measured in annual rings, pith, bark, and leaves of five tree species from a highly contaminated site with As [25]. The highest concentrations were found in bark and leaves; tree-ring As levels were low but still considerably higher than those from the control areas.

Two possible ways to dispose CCA-treated wood in USA are landfilling with municipal solid waste (MSW) and waste-to-energy (WTE) facilities. These disposal methods have been compared in terms of environmental impact [26]. Advantages of WTE are that less landfill area is required, it produces energy and it does not imply fossil carbon emissions. But WTE is more expensive than MSW and it releases more chromium from the ash on an annual basis. On the other hand, CCA-treated wood in landfills has been found to increase arsenic and chromium concentrations in leachate.

Related to investigation on natural wood preservatives, in teak wood the main chemical which imparts decay resistance against two brown-rot fungi was identified as napthoquinone [27].

VOC – Volative Organic Compounds Emissions and General Air Quality

VOC's main sources of emissions in the forest products industry comprise timber drying kilns, driers of wood panel furnish, either particles, wafers or fiber, and hot presses for panel production. Also, VOC's may have their origin in wood or in the binder of wood-derived products. Among the complex mixture of chemical compounds that make VOC's, formaldehyde has been the one that poses more concern about impact on human health.

Formaldehyde has its origin in the binder matrix of a wood product in cases when the binder, or resin, was prepared with formaldehyde (F) together with other chemicals. The most important of these chemicals for production of resins at industrial level are urea (U), melamine (M) and phenol, for the so-called UF (urea-formaldehyde), MUF (melamine-urea-formaldehyde), MF (melamine-formaldehyde) and PF (phenol-formaldehyde) resins. If a given resin was not prepared with formaldehyde, as it is the case of MDI (methylene-diphenyl-isocianate), then formaldehyde emissions are much lower, and must be originated in the wood. Many natural substances, other than wood, contain formaldehyde. This explains why research on adhesives has been focused on formaldehyde-free resins, and, on the other hand, on resins prepared with natural and renewable chemicals.

Lignin-based wood adhesives have been prepared without formaldehyde, being this chemical replaced by glyoxal [28]. Particleboard panels manufactured with this new adhesive passed relevant standard specifications, and the adhesives showed sufficient reactivity to yield panels in press times comparable to those of formaldehyde-based commercial adhesives.

As mentioned above, wood contains detectable formaldehyde sometimes enough to be significant to contribute to formaldehyde emission levels from wood products. The variation of formaldehyde contents in important commercial wood species that are dried and ground to wood particles for wood-based panel production has been studied [29]. Results indicate that formaldehyde varied up to 4-fold across commercial softwoods and hardwoods, but remained at low concentrations (under 1 mg/100 g).

Fiber for MDF, either produced by the chemo-thermo-mechanical technique (CTMP process) or by the thermo-mechanical technique (TMP process), has been studied for its formaldehyde and other VOC content [30]. The CTMP showed lower emissions of formic acid and formaldehyde; but a higher emission of acetic acid was measured as compared to TMP.

Creosote-treated timber is a source of VOC's. The main components of the vapors released from creosote-treated wood have been identified and the concentrations in the air nearby were measured on the day of the treatment and after 8 days [31]. Such concentrations, total VOC's, were respectively 35 and 5 mg/m^3.

More than impacts on human health, VOC emissions concern also environmental quality, mainly in the air. Lower emissions to the atmosphere may be reached by reduction in the source or by their abatement with control equipment. The more usual process to reduce the concentrations of VOC's in a gaseous emission is thermal oxidation. Because thermal oxidizers consume large quantities of energy and are expensive to operate, alternatives have been sought. A lab-scale absorption system has been presented [32], and is based on an absorption system using a room temperature ionic liquid (tetradecyl(trihexyl)phosphonium dicyanamide) as the absorbant.

Suspended dust in air is also harmful to humans, and concentrations in workplace can be several folds higher than those in the open atmosphere. Some factors that influence the size of dust particles emitted from CNC (Computer Numerical Control) MDF milling have been studied [33]. The most important factor affecting the amount of dust created from milling was average chip thickness. Hence, in order to reduce the amount of dust, it has been recommended that milling parameters should be chosen so that the average chip thickness is greater than 0.05 mm.

Adhesion

Wood adhesives applied today at industrial level, and for decades, are made of chemicals derived from oil, which has been the origin of much concern about sustainability, and also about price, each time it happens an oil crisis. This is why research has been active in preparing resins/adhesives based on natural and renewable products. Plant extracts, namely tannins, have been the main important source of natural products for adhesives, and reached the industrial production several decades ago. But research with renewable products continues. Hahn and Gindl [34] developed a new procedure for bonding particleboards using animal protein produced from bone. Panels with mechanical properties comparable to the MUF-bonded ones were manufactured. This result was attributed to the thermoplastic properties of bone glue.

Regarding concerns with air pollution caused by VOCs emission, of which formaldehyde has been the most important chemical, binderless adhesion seems particularly attractive to avoid those kind of emissions. The most recent research results in this area revealed that edge-to-edge linear vibration welding of particleboard, OSB, MDF, and plywood, gives better strength than face-to-face panel welding [35].

Storage of Wood Issues

The runoff from wood handling sites can be a source of pollution. The principal environmental problem lies in the high concentration of organic substances, originating from the wood and bark, being some of them toxic to aquatic life [36]. Methods used to reduce the negative environmental impact of the runoff are constructed wetlands, soil infiltration and chemical oxidation.

LCA – Life-Cycle Assessment

A review of existing life-cycle assessments (LCA) on paper and cardboard waste revealed that a broad consensus was found, despite differences in geographic location and definitions of the paper recycling/disposal systems studied, that there are environmental benefits in recycling over incineration or landfill options [37].

After a review of LCA of windows [38], it was concluded that in all LCA's that considered frame materials, wood had lower embodied energy than the market alternatives. Moreover, the primary determinant of a LCA advantage stems from a longer service life and lower replacement frequency.

After an assessment of the environmental impacts during the life cycle of hardboard (wet-process fiberboard) manufacturing [39], it was concluded that reductions of toxic emissions during drying, mat forming and binder production are desirable. And that it is possible to improve the environmental performance of the hardboard manufacturing process if some alternatives are implemented regarding the use of chemicals, electricity profile and emission sources.

Sequestration of Carbon

An estimation of the contribution of harvested wood products (HWP) in USA to annual greenhouse gas removals in the agriculture, forestry, land use, and land use change sector [40], concluded that HWP would offset 42% to 61% of residential gas C emissions in 2005.

Discussion

Concerning recycling of lignocellulosic wastes or subproducts, research continues on replacing wood raw materials by agriculture residues to make panels, namely particleboard and MDF. Examples of low-value raw materials are beetle infected wood and fire-killed trees. Cement composites are a good way to include some residues, like ash.

In the field of wood protection/preservation there is great concern about any impact on human health derived from the utilization of CCA-treated wood structures, namely in playgrounds. Such concern extends to the mobility, i.e., leaching, of CCA constituent elements (chromium, copper and arsenic) into the soil, and to the determination of the concentration in soil of those elements. Methods for the disposal of CCA-treated timber and their environmental impacts have also been assessed.

To avoid VOC emissions to the atmosphere, resins without formaldehyde continue to be developed, and formaldehyde originated in wood has been measured. Measurements of wood dust concentration in workplace have been undertaken, and measures to lower its levels have been suggested. Concerning adhesion, adhesives based on renewable and natural products continue to draw the attention of scientists, and bonding by wood welding continues to be studied.

Storage of wood can have a significant negative impact on environment, namely aquatic courses or lagoons, because of runoff with a high concentration of organic substances.

LCA is the true assessment of environmental performance of products and processes. Paper recycling has advantages over incineration and landfill options; wood-framed windows have a lower embodied energy; and some suggestions to diminish negative environmental impacts of hardboard manufacturing have been given. Sequestration of carbon is a very important issue nowadays; an estimation of the contribution of harvested wood products in USA to annual greenhouse gas removals has been done.

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