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A Comprehensive Review on Waste Generation, Management and Environmental Effects in The Plywood Industry

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KEYWORDS

plywood industry, waste management, formaldehyde, wood dust, VOCs, wastewater treatment, life-cycle assessment, occupational exposure

ABSTRACT:

Plywood industry is a major industry in the global wood-processing industry that provides engineered wood products in the construction, furniture and packaging. However, another plywood manufacturing generates different types of wastes-solid, liquid, gaseous and adhesives and chemicals that may pose health hazards to their environment and health. The review is a summarization of the literature that exists regarding the generation of waste in plywood mills, the character of the largest waste products (sawdust and wood residues, adhesive residues and sludges, wastewater contaminated with phenols and formaldehyde, and gaseous emissions containing volatile organic compounds), waste treatment and management methods, the environmental impact of the life-cycle, regulations, and mitigation technologies. The most important mitigation measures are resource-efficient mill layout, residue valorization (energy recovery, particleboard reprocessing, briquetting), advanced wastewater treatment (physical-chemical system, biological system), low-emission adhesives and process optimization to reduce VOCs and formaldehyde emissions and occupational controls to limit the exposure of workers to the wood dust and toxic emissions. The gaps which remain in the critical knowledge regarding the standardized reporting of the waste quantities and effectiveness of waste management in various regions, long-term monitoring of groundwater in the surrounding of mills and life-cycle comparison of other adhesive systems. In this paper, recommendations of industry best practice, research agenda and policy interventions have been provided to restrict the environmental footprint of plywood production.

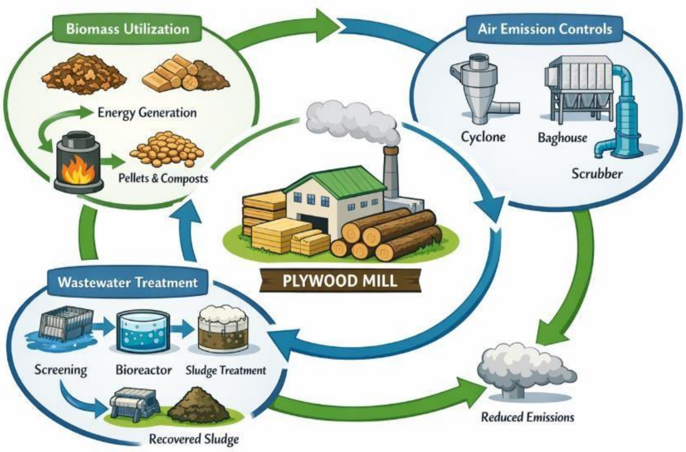

Figure 1. *Graphical Abstract*

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1. Introduction

Plywood is considered one of the cornerstone products of the wood-based panel industry since it has a high strength-to-weight ratio, reasonable levels of dimensional stability, and relatively low price, which contributes to its popularity in construction and furniture projects (Papadopoulos, 2010; Mantanis et al., 2017). Nonetheless, plywood production also results in the formation of solid, liquid and gaseous wastes that may cause environmental burden and quantifiable health hazards in case they are not properly curbed. Common solid wastes in the form of sawmill and veneer-processing wastes such as sawdust, shavings and veneer offcuts, and resin handling and glue spreading may result in adhesive residues and sludge. Depending on the adhesive system and process conditions, liquid effluents can also include remaining resin related-constituents (such as phenolic compounds and formaldehyde-related fractions), and air emissions usually include volatile organic compounds (VOCs) and wood dust which has been abrasive during the trimming, sanding, and finishing processes (Huang et al., 2017; Roffael, 2016; Salthammer et al., 2010). Formaldehyde has long been pointed to as a primary issue of concern in relation to wood based panels based on both indoor air and material-emission studies, which have implications on both occupational hygiene and indoor air quality of the community at large (Kim, 2009; Salthammer et al., 2010). Similarly, occupational health sources and risk assessments have identified wood dust exposure as a major work-related risk up which needs to undergo regular system engineering controls and surveillance (Demers et al., 1995; IARC, 2012). Here, it is important to know the waste composition, rates of generation, how it affects the environment, and treatment efficacy in order to mitigate the effects and safeguard workers and the local societies.

The literature review is a compilation of peer-reviewed literature, technical reports, and regulatory guidance that offers a comprehensive report of the waste generation and mitigation in plywood production with a focus on the impacts of uncontrolled or under-controlled releases and the effectiveness of the accessible treatment methods. In line with the overall literature on environmental assessment of wood products and panels, the review shows that a combination of source-reduction measures (process optimization, material substitution, and housekeeping) along with end-of-pipe measures (effluent treatment and emissions capture) are the most reliable as compared to a single intervention (Gonzalez-Garcia et al., 2011; Werner et al., 2010). Thus, the review uses empirical evidence (measured VOC profiles and reported treatment outcomes) to define technologies that have proven efficiency and map unresolved gaps in the research, especially associated with integrated pathways to wood residues waste minimization and circular economy (Geissdoerfer et al., 2017; Kirchherr et al., 2017).

2. Methods and Scope

This review is based on the systematic and extensive analysis of scholarly, technical, and regulatory literature pertinent in generating waste, waste management practices, and their environmental effects in the plywood industry. The peer-reviewed journal articles, conference proceedings in the fields of environmental engineering and wood science, doctoral dissertations, government technical bulletins, and guidelines of international agencies were used as the main sources of evidence. The focus was directed on interdisciplinary sources on wood technology, environmental science, occupational health, industrial ecology, and wastewater engineering to provide a comprehensive view on the topic. The strategy of literature search was structured to provide the coverage of the topic in a broad but focused way. Key Scientific databases like Scopus, Web of science, science direct, springerlink, and Google Scholar were searched by applying a combination of targeted keywords and Boolean operators. The main keywords were used, i.e., plywood wastewater, formaldehyde emissions plywood, wood-based panel VOC emissions, sawdust reuse plywood, wood dust occupational health, phenol-formaldehyde resin effluent, industrial wastewater treatment wood industry, and life cycle assessment wood panels. These words have been chosen to get process-specific environmental burdens as well as general sustainability assessment. Other searches were done using regional identifiers to find case studies in the large plywood-producing nations in Asia, Europe, and South America.

Preference was also given to those studies that are published within the past 20 years in order to be in line with the technological changes in the field of adhesive chemistry, pollution control systems, and the method of life-cycle assessment. Previous background literature was however also considered whereby they presented the necessary background information on waste characteristics, toxicological characteristics of formaldehyde, or even early industry treatment processes that are still popular in the modern world. Articles that have empirical research and reported measured concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), phenolic compounds, volatile organic compounds (VOCs) and particulate matter were of particular interest. These empirical studies made it possible to make quantitative comparisons of waste profiles and treatment efficiencies across the various mill setups as well as geographic settings. Besides peer-reviewed literature, international guidance documents and regulatory frameworks were also examined to put environmental management into the backdrop of current policy settings. The reports of various organisations like the United Nations Environment Programme (UNEP), the Food and Agriculture Organization (FAO), the International Labour Organization (ILO) and national environmental protection authorities were studied to learn about the best practices in the world and the level of emissions. These reports gave an understanding of the formaldehyde emission limit to wood panels, occupational limit to the exposure of the wood dust and VOCs, and effluent limit to industrial wastewater.

3. Overview of Plywood Manufacturing and Typical Waste Sources

Plywood manufacturing is an industrial process that consists of many stages during which raw timber is processed into engineered panels by a series of mechanical operations and thermo-chemical operations. The value of each step is not only the formation of the product, but also the formation of certain streams of waste which vary in their physical state, chemical composition, and the possibility of impact on the environment. These streams of waste must be understood in detail to enable effective management strategies to be designed. It starts with the procurement of logs, storage, and debarking. The logs tend to be stored in open yards whereby the rain runoff may carry the bark pieces, soil particles, and organic matter to the adjacent drainage system. Debarking leaves large amounts of bark residues that are mostly coarse and fibrous. Although bark is commonly reused either as boiler fuel or landscaping material, it can lead to leachate formation that has tannins and organic acids especially when not stored correctly. In rotary peeling, logs are fastened on a lathe and spun against a cutting blade in order to cut continuous pieces of veneers. This phase produces veneer clippings, ribbon-like offcuts, core plugs and rejected veneer sheets because of the defects like knots or splits. Due to the high levels of dependency on the log diameter, wood species, and precision of equipment, the recovery rates are highly diverse. In most traditional types of plywood factories the total recovery rates of the wood can be lower than 50 percent, which implies that almost half of the received biomass is residue. In spite of this material being technically reusable, due to poor handling or absence of valorization infrastructure, the material may end up being disposed of in an unwarranted manner. Veneers drying is an energy-consuming process that may result in solid and gaseous wastes. Veneer sheets are also subjected to dryers to remove the content of moisture to the point where it can be bonded with adhesives. Small pieces fall off during the drying process, and this is added to fine woods. Simultaneously, natural volatile organic compounds in wood, including terpenes and extractives, are discharged to the atmosphere together with the byproducts of combustion, in case fossil fuels are employed to produce heat. Such emissions can help in degradation of the local air quality unless they are captured well.

The gluing and lay-up process brings about the synthetic resins into the production cycle. Common resin systems that are used to treat the veneer surfaces are urea formaldehyde (UF), melamine formaldehyde (MF), phenol formaldehyde (PF) and hybrid or modified resin systems before assembly. This step produces adhesive wastes due to over-application, spillage and cleaning of equipment. Pipelines and mixing tanks must be washed regularly which results in wastewater streams that are contaminated with the residual monomers, phenolic substances and suspended solids. The adhesive sludge may also be deposited in storage tanks and settling basins and they will likely have partially polymerized resin, fillers and unreacted chemicals.

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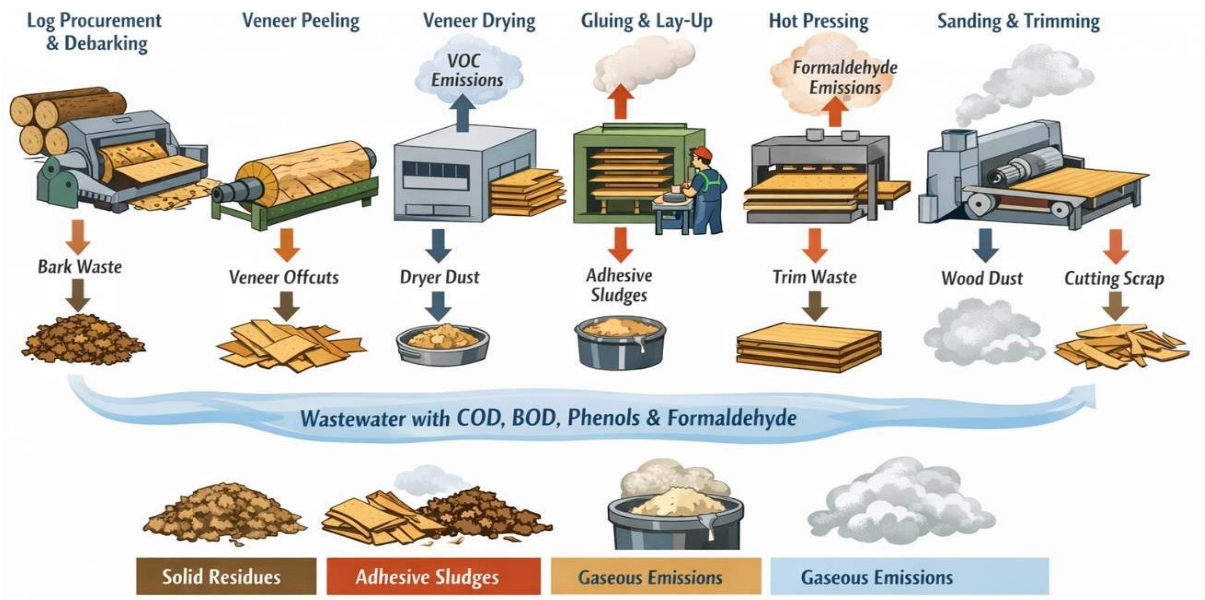

Figure 2. *Schematic of plywood manufacturing steps and associated waste streams (solid residues, wastewater, gaseous emissions, adhesive sludges).*

These wastes are complex chemically and could be toxic because of the traces of formaldehyde or phenol. The improper disposal may lead to the contamination of soil and groundwater.

Table 1. *Typical plywood mill waste streams and characteristic constituents (illustrative ranges).*

Waste stream	Typical constituents	Representative concentration / comment
Veneer trims & sawdust	Cellulose, lignin, residual adhesives	High calorific value; particle size variable
Sanding dust	Respirable wood dust, wood extractives	Hazardous to respiratory health
Wastewater (process)	Suspended solids, COD/BOD, phenols, formaldehyde, ammonia	COD and phenol spikes during resin washouts; pH variable
Adhesive sludge	Resin fragments, unreacted formaldehyde, phenol	Requires stabilization/secure disposal
Gaseous emissions	Formaldehyde, VOCs, terpenes, particulate	Indoor air and community exposure concerns

4. Quantities and Composition of Waste

The quantitative estimates of waste generated per unit of plywood made differ widely basing on many inter related factors such as species of wood, log diameter, peeling technology, efficiency of the plant, adhesive system, internal recycling practiced within the mill among others. The manufacturing of veneer-based panels is linked with material waste as the rotary peeling process results in side trims, ends of ribbons, core plugs, and damaged sheets of various rejects depending on knots, splits, and decay, or irregularities in thickness. In contrast to the manufacturing of particleboard or medium-density fiberboard where the particle and fibre wood can be reconstituted with little geometric constraint, plywood manufacturing needs intact veneer sheets of a particular size and quality. This leads to reduced recovery rates, and a greater proportion of the present biomass is residue.

In traditional plywood processes, total wood recovery can be between 45-65 percent (based on the quality of logs and modernization of the plant). Older or smaller mills have less accurate peeling lathes and manual grading systems, and then they are more prone to high rejection rates. When it utilizes lower grade logs, the veneer clipping and sorting losses go even higher. Also, post-press operations involved in trimming also lead to secondary losses especially when it comes to cutting panels to standard market sizes. When these residues are not directly disposed, they constitute diversion of the material to the main product stream.

Journal of Chemical Health Risks
www.jchr.org
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The international reviews such as those by international forestry and industrial development agencies have continued to underline that these residues are a huge untapped resource. Core plugs, veneer offcuts, bark and sanding dust have significant calorific potential and can be utilized as biogas to produce steam and heat to veneer drying and pressing processes. In others, the residues are chipped, provided to particleboard or fiberboard manufacturers, and thus interindustry flows of materials are supported. Nevertheless, there is a great range of efficiency with respect to residue utilization. Complete or near-complete reuse of solid wood residues can be realized in large-scale integrated industrial clusters, but in small or geographically remote facilities, residues can be stored in the storage yards, which can be exposed to fire hazards and release leachates when it rains.

The mass balance point of view shows that solid residues usually weigh the most, but liquid wastes are disproportionately hazardous to the environment due to the chemical structure of the wastes. The rate at which wastewater is produced is highly reliant on the process water management strategies. Mills that have closed loop water systems and recycling measures produce very low volumes of effluents compared to the plants that use once-through washing procedures. However, despite using plants that are water efficient, cleaning of adhesive mixing tanks, pipelines of resin and equipment used in pressing introduce the wastewater system to periodic streams of chemically polluted water.

Empirical analyses of wastewater always indicate a high value of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) with a high value of above several thousand milligrams per liter in un-treated effluents. A high BOD represents the existence of biodegradable organic material whereas high COD represents the existence of biodegradable and non-biodegradable oxidable compounds. Such organic loads are the dissolved wood extractives, carbohydrate fragments, resin components and wash water residues. Phenolic compounds especially in mills using phenol formaldehyde resins are a source of toxicity and recalcitrance. Any leftover traces of formaldehyde can be also found, particularly in the places where urea formaldehyde adhesives are very common. Moreover, there might be nitrogencontaining and ammonia on the basis of resin chemistry and degradation products of wood.

5. Environmental and Health Impacts

5.1 Water Quality and Aquatic Ecosystems

Plywood manufacturing facilities may release untreated or insufficiently treated effluents into the water bodies and this can seriously interfere with the ecological balance of such bodies. The first effect is the increase in the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Large amounts of biodegradable organic matter in the form of large amounts of biodegradable organic matter are indicated by the presence of high BOD which is utilized by the microorganisms during the decomposition process. Dissolved oxygen (DO) in water is eliminated as the microbial activity increments. A drop in DO below critical levels causes stress, retarded growth or death of aquatic life including fish, invertebrates and the aerobic micro-organisms. The long-term hypoxia or even anoxia may take place due to oxygen deprivation that will radically change the aquatic ecosystem.

The chemical oxygen demand indicates the biodegradable and non-biodegradable oxidizable materials. They are dissolved wood extractives, pieces of resin, phenols, and left-over adhesives in plywood effluents. This is indicated by high values of COD which implies that there is a high load of pollutants that might not be cleared off even after partial biological treatment. Released into rivers or lakes, these compounds are stored in sediments that extend the contamination beyond the time when they have been discharged.

A special concern is given to phenolic compounds. Even in relatively low levels, phenols toxic to aquatic organisms and may have significant odors and flavors in water therefore unsuitable as domestic water. With prolonged exposure the reproduction and growth of aquatic organisms can be affected. Additionally, certain phenolic derivatives are bioaccumulative, and this may be risky along the food chain. Unused formaldehyde in effluents aggravates the problem. Formaldehyde as a reactive aldehyde is dangerous to aquatic lives and may be a source of cellular damage to affected species. Even though it can decompose in time, the continuous release can sustain the detrimental levels in the local areas.

5.2 Air Quality: VOCs and Formaldehyde

The major sources of formaldehyde and other volatile organic compounds (VOCs) are the process of adhesive preparation, hot pressing and the beginning of panel storage when the resin curing reactions are in progression. The rate of emission depends on the type of resin used, the temperature applied during pressing process, the thickness of the panel used, and the time allowed in the post production conditioning. Studies show that not all bio-oil systems or modified resin systems can lower the concentration of free formaldehyde, but they can also bring about the new VOC species species, changing the overall emission spectrum instead of entirely removing it. The constant observation, better air ventilation, low-emission resin formulations, and correct circumstances of product curing and storage are thus necessary to reduce the risk of exposure to the occupational and environmental factors.

5.3 Occupational Health: Wood Dust and Chemical Exposures

It is well known that inhalation of wood dust is a serious occupational health risk in both plywood and other wood-processing industries. Fine particulate matter is released into the air during the cutting, trimming, sanding and finishing processes and may be left hanging in the air in the workplace. The smallest of them, commonly so called respirable dust, can get inside to the deepest parts of the lower respiratory tract and reach the bronchioles and alveoli. The chronic bronchitis, the symptoms of asthma, the irritation of the nose and the lowered lung functioning have been associated with repeated exposure to such particles. It has also been found by scientific research that exposure to wood dust during prolonged periods may cause inflammatory reactions and augmented oxidative stress in lung tissues, which may result in long-term breathing loss.

Chemical exposures further increase the risk of health in addition to mechanical irritation by dust particles. The vapours of formaldehyde that are emitted by adhesives during pressing and storage can cause irritation of the eyes, nose, throat, and skin at relatively low levels. Exposure to benzene in the short-term will cause watery eyes, coughing, and sore throat, whereas prolonged exposure could increase the likelihood of developing chronic respiratory illnesses. Phenolic compound (some resin systems include this) may lead to mucous membrane irritation and skin sensitization, as well. These effects vary in their severity depending on the level of exposure, time taken, effectiveness of the ventilation in the workplace and the regularity of the use of personal protective equipment.

5.4 Climate and Resource Impacts

By the life-cycle view, wood panels like plywood are usually said to be beneficial in the environment due to the fact that biogenic carbon that is absorbed in trees during the growth process is stored in the wood. Carbon is held in the panel during service life, which in the shortterm postpones its emission back into the atmosphere. This carbon storage effect is beneficial to the reduction of climate change when it is obtained in a sustainably managed forest, particularly when wood products replace more carbon-intensive substances like concrete, steel, or ceramics.

Nevertheless, the total sustainability of plywood cannot be measured based on carbon storage only. The results of life-cycle assessment (LCA) studies continue to reveal that upstream and manufacturing phases have a huge impact on overall greenhouse gas emissions. Manufacturing of adhesives, especially used in the production of synthetic resin such as urea–formaldehyde and phenol formaldehyde, is a significant source of fossil-based emissions through the use of petrochemical feedstock and highly energy-demanding production processes. Likewise, drying and hot pressing of veneer consume a lot of thermal energy, which can be produced by fossil fuels in areas where there is no integration of biomass energy.

The climate profile also is determined by waste management practices. The use of wood residues on-site as an effective energy source can be used to compensate the use of fossil fuels, which will lead to better net emissions. In addition, the impact of regional electricity mixes is very strong; due to the high proportion of renewable power plants in geographic areas will tend to have smaller embodied emissions. In turn, the LCA comparisons demonstrate the inconsistency in terms of the panel subtypes, geographic locations, and resin formulations, which emphasizes the need to evaluate the context-specific environmental issues.

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 225-237 | ISSN:2251-6727

6. Waste Management and Treatment Options

The plywood industry can be considerably structured concerning waste management in terms of three interconnected strategic directions that implement an integrated environmental control model. The former is more focused on reducing the sources and optimizing the processes, which seeks to reduce the waste production at the source by more efficient veneer recovery, more accurate adhesive application, more efficient water management, and more efficient drying systems. The second strategy focuses on the valorization and reuse of residues, i.e., transformation of the wood offcuts, bark, and sawdust into energy, secondary products or raw materials used by other panel industries. The third strategy will be end-of-pipe treatment and safe disposal where all wastewater, emissions, and dangerous residues undergo treatment prior to release into the environment.

6.1 Source Reduction and Process Optimization

Optimization of the processes is important in reducing the production of wastes and the effect on the environment through plywood manufacture. Optimisation of veneer recovery by means of fine-controlled peeling, improvement of log conditioning, and the use of better scanning technology has lowered the amount of trimming loss, and raised the ratio of usable veneer to each log. The meticulous use of adhesive application, particularly, the control of the spread rate and automated dispensing glues, is used to minimize the excessiveness of resins, thus reducing the waste of the material and further emissions as well. Wash water used in the preparation of glues and cleaning of its equipment is captured, filtered and reused to reduce the amount of wastewater and the amount of pollutants discharged. Further, the fuel use and the resultant air emissions can be reduced by retrofitting to veneer dryer with lower energy consumption and better drying schedules.

In addition to the mechanical enhancements, resin chemistry development also helps in reducing emissions. Replacement of traditional high-emission adhesives with less formaldehyde structures or adjusted structures like phenol resorcinol urea formaldehyde (PRUF) resins can minimize the release of free formaldehyde and still maintain bond strength, longevity and structural efficiency of completed panels.

6.2 Solid Residue Valorization

Veneer trims and sawn dust produced in the process of making plywood offer a great prospect of sustainable reuse instead of disposal. These residues are rich in calorific value and thus can be used as direct fuel in industrial boilers or turn them into pellets and briquettes that can be used in an efficient way to produce energy. Most mills incorporate biomass-fired systems which use internal residues to produce steam to dry veneers and hot press, thus minimizing the use of fossil fuels and minimizing greenhouse gas emissions. Wood residues can also be used in the production of particleboard, fiberboard, or composite materials in addition to energy recovery, fostering the use of circular material flows in the wood industry. Following suitable treatment, some wastes can also be reused as soil improvers or fed on creating bio-based products that are emerging like biochar, activated carbon, or biochemicals. Technical reviews underline that the strategies of valorization of this sort can lead not only to decreasing the amount of waste but also increasing the economic efficiency and ensuring the sustainability of operations in the long term.

6.3 Wastewater Treatment

The treatment of wastewater in plywood manufacturing plants is usually done in a multistage or staged manner, which is aimed at gradually eliminating the solids, organic material, and toxic elements. The first process is normally primary or physical treatment, which entails screening and sedimentation. Screens eliminate coarse materials (wood chips, bark pieces, adhesive clumps etc) and settling tanks decrease the total suspended solids (TSS) by separating them through gravity. As much as this measure reduces turbidity and load of particles, it does not go a long way in controlling dissolved contaminants.

The chemical treatment that follows usually includes coagulationflocculation and pH correction which is usually done using lime or other alkaline agents. The lime treatment has the ability to induce the precipitation of some phenolic compounds and improve the filtration of suspended solids and part chemical oxygen demand

Journal of Chemical Health Risks
www.jchr.org
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(COD). Nevertheless, although empirical research indicates quantitative decreases in the pollutant levels, this approach in itself seldom can meet the strict discharge regulations, especially of dissolved organics and residual formaldehyde.

Activated sludge processes or sequencing batch reactors are then used to treat the biodegradable organic fractions, and to decrease the biochemical oxygen demand (BOD). At high levels of phenol though, microbial activity can be suppressed and thus some dilution or pretreatment is required or acclimatized microbial consortia can be used. Another polishing step that is added to more recalcitrant compounds is advanced oxidation processes and membrane filtration. According to recent assessment, integrated hybrid systems that are based on a combination of physico-chemical and biological treatment can be used to ensure the most credible performance of complex plywood effluents.

Table 2. *Wastewater treatment technologies for plywood mill effluents (overview).*

Technology	Applicability	Typical removal / notes
Screening & sedimentation	Primary solids removal	Removes coarse solids and reduces TSS
Coagulation/ flocculation (lime, alum)	Phenols, suspended solids	Partial phenol/TSS/COD reduction; performance varies.
Activated sludge / SBR	Biodegradable organics	Effective for BOD; phenol inhibition possible
Advanced oxidation (Fenton, ozonation)	Recalcitrant organics	Good for phenol/formaldehyde; cost and byproducts must be managed
Membrane filtration	Polishing and solids separation	High-quality reuse but fouling is a concern

6.4 Air Emission Controls

The efficient air emissions control in the process of plywood production is based on a set of the engineering solutions and the replacement of materials. Enhanced enclosures of processing equipment especially sanding, trimming, and hot press stations, contain the origin of airborne contaminants. The local exhaust ventilation systems that have high-efficiency capture hoods harness wood dust, formaldehyde gasses and other volatile organic substances before they spread into the overall working atmosphere. Those gaseous emission formed in the course of resin curing are usually treated by thermal oxidizers and catalytic oxidizers to decompose VOCs and formaldehyde into less toxic products, which include carbon dioxide and water vapor. Activated carbon adsorption systems can capture volatile compounds before releasing them into the atmosphere in intermittent or low concentration conditions of emissions.

In addition to process controls, off-gassing of completed panels can be managed by ensuring that these panels are stored in places that are well-ventilated to ensure that there are no issues with indoor air quality in the downstream applications. Measurement studies have always revealed that the best approach to reducing occupational and community exposures is the pooling of low-emitting adhesive formulations with sound engineering controls.

6.5 Occupational Controls

It is important to introduce an elaborate occupational health precaution in the plywood manufacturing industries whereby air pollutants are emitted. Ambient concentrations of particulate matter are notably decreased in sanding, cutting and trimming stations by highefficiency dust collection systems. Workers can be exposed to the respirable wood dust and chemical vapors when fitted with respiratory protective equipment and reduced to a minimum level. Regular surveillance programs, such as pulmonary function testing and symptom tests allow respiratory impairment to be detected early and used to help guide the corrective interventions. The constant air monitoring at the work place will guarantee adherence to the occupational exposure limits, as well as the locations that need better ventilation. In combination with engineering controls (e.g., equipment enclosure and local exhaust system) and administrative controls (e.g., safety education and rigorous management of exposures), the administrative controls (e.g., safety education and rigorous control of exposures) significantly reduce the health risks and enhance the long-term well-being of workers.

Journal of Chemical Health Risks
www.jchr.org
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7. Life-Cycle Considerations and Comparative Assessments

Life-cycle analysis (LCAs) always demonstrates that plywood and other wood-based panels have climate benefits over most other mineral-based construction materials, in large part because of the storage of biogenic carbon. During the growth, trees absorb carbon dioxide in the atmosphere, and the carbon is stored in wood products as long as the products are in service, hampering their emissions into the atmosphere. This carbon cycle can have a positive impact on the climate mitigation in the long-term when forests are managed in a sustainable way and harvesting is accompanied by the regrowth.

However, manufacturing parameters are very sensitive to the overall performance of plywood regarding environmental performance. The process of making adhesives is also important since the creation of resins can be associated with fossil fuel usage and energy-consuming technologies. Likewise, veneer drying and hot pressing demand high thermal energy and the carbon intensity of the energy depends on local fuel supplies. The destiny of wood remnants also has a role to play; when the remnants are exploited to recover energy, they are able to eliminate the use of fossil fuels. In turn, the revision of LCA focuses on the active inclusion of the use of residues and on-site energy systems under the scope of assessment in order to represent the practices of a circular industry.

8. Policy, Standards and Regulatory Frameworks

There are vast differences among the regulatory systems that define environmental performance of the plywood industry in various countries, which are influenced by differences in economic capabilities, industrialization and health concerns of people. Various jurisdictions have set product emission standards such that the quantity of formaldehyde that emits out of finished wood panels is restricted, especially when it comes to materials that are used in indoor spaces. Such standards are normally supplemented by workplace exposure limits that govern the concentration of airborne formaldehyde and wood dust to ensure the health of the employees is not put at risk. Moreover, environmental protection regulatory bodies usually provide wastewater discharge provisions, which stipulate acceptable levels of the biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, and the phenolic compounds in effluents discharged to surface water or municipal treatment plants. The solidwaste management laws can also lay down that adhesive sludge and contaminated residues should be properly handled and disposed to avoid contamination of soil and groundwater.

International guidance documents give more general frameworks that countries may use when formulating or revising national policies. Nevertheless, it has been difficult to implement on the regions where the small- and medium-sized plywood mills prevail, as financial limitations do not allow investing in new sophisticated treatment technologies. Such policies as technology transfer schemes, low-interest financing, tax exemptions, and centralized or cluster-based effluent treatment plants would be effective tools of enhancing compliance, environmental performance and retaining industrial viability in such situations.

9. Case Studies and Regional Practices

Practicum evaluation of experimental environmental treatment of plywood mills indicates that technological efficacy has a close connection with the extent of monetary investment as well as the stringency of regulation. Within a facility where environmental compliance is proactively maintained and is supported in terms of capital allocation, the pollution control systems will always have higher removal efficiencies and consistent performance. On the other hand, where resources are under-allocated or such enforcement mechanisms are weak, treatment systems can be poorly maintained, operated poorly, or not used at all leading to inconsistent outcomes.

A close examination of lime treatment of effluents delivered by effluents treatment unit in melamine-urea-formaldehyde (muF) and phenol-formaldehyde (PF) resin manufacturing facilities showed quantifiable reductions in suspended solids, some fractions of phenols, and part of chemical oxygen demand. Nevertheless, even with these advances, in many cases, with lime treatment as a standalone method, the concentration of pollutants were still in excess of high levels of discharge. The above observation highlights the need to use multi-stage treatment trains with biological and/or high-level oxidation processes to meet regulatory compliance.

Individual investment in an extensive treatment system may not be economical in areas where there are many small-scale plywood producers. Cluster based solutions such as centralized effluent treatment plants (CETPs) and common biomass energy plants have been developed into cost effective solutions. Through the sharing of capital and operational expenses across several mills, this type of collaboration enhances the environment and maintains the Industrial competitiveness.

10. Research Gaps and Priorities

The future development of the plywood industry in terms of minimizing environmental footprint relies on the ability to meet some of the key research and implementation priorities. Among the key requirements is that they should develop standardized waste generation reporting framework. Representation of the quantities of waste in uniform units like mass unit per square meter of completed panel or unit of veneer processed would allow significant cross-facility, cross-regional, and cross-technological benchmarking. In the absence of harmonized metrics, comparisons will be hard and will not allow determining the best performing plants or setting realistic improvement goals.

Another necessary priority is long-term monitoring of the environment. The large-scale plywood production areas can have cumulative effects on the surrounding ground water table and surface water system as a result of old discharge methodology, the unlined solid waste storage, and the unintended discharges. Multi-year and systematic programs of monitoring are needed to measure the tendency in the pollutant levels, identify delayed contamination, and determine the recovery of the ecosystem after the introduction of better treatment systems. This type of data would also make the regulatory decision-making and confidence to the people stronger.

Parallel to this the comparative life-cycle analyses of the developing low-emission adhesive systems should also be further addressed. Alternatives to phenolic formulations such as biobased adhesives or modified phenolic formulations are advertised as being environmentally friendly in terms of their manufacture but a complete LCA will need to consider not just manufacturing emissions, but service life, durability, end-of-life disposal or recyclability, and even the potential toxicological effects. Trade-offs can be comprehended only by the help of complete life-cycle assessment.

Economic viability has been a major limitation especially among the small and medium businesses. Residue valorization strategies such as energy recovery and the development of secondary products should be evaluated using cost benefit analysis to come up with pragmatic adoption routes in low capital scenarios. Lastly, the hybrid wastewater treatment systems that combine cost-effective pretreatment and biological and oxidative polishing should be tested on a field-scale to verify the performance, operational stability, and low cost in various regional conditions.

11. Recommendations and Best Practices

Suicide bombers committed to destruction are also using the wood-processing industry as a source of income.To enhance the sustainability and environmental conformity in the woodprocessing industry, a well-coordinated and future-oriented approach is very crucial to the industry managers, regulating bodies, and policymakers. To start with, process-level improvements should be prioritized and this should be focused on eliminating waste at the point of production. These involve maximizing the recovery of veneers with accuracy cutting and grading technology, developing the best application systems of adhesives that reduces unnecessary usage and emissions, and a closed loop water recycling system that helps a lot in terms of freshwater usage and wastewater emissions. Simultaneously, it is essential to invest more in residual valorization. By-products like wood offcuts, bark, sanding dust and other byproducts can be channeled to on-site energy recovery systems like biomass boilers or can also be used as feedstock in the manufacture of particleboard and other composite products. This minimizes the use of landfill besides offering a source of process heat, which is renewable, enhancing the efficiency of energy in general.

Wastewater management should also be enhanced by adopting combination treatment system e.g. primary

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 225-237 | ISSN:2251-6727

sedimentation, biological treatment and advanced oxidation systems that would depend on the particular effluent nature of a given facility. Handling and disposal of sludge of residual formaldehyde or any other contaminant should be strictly followed in order to avoid secondary contamination. Moreover, the shift to the less emitting or bio-based adhesives should be highly sought where it is technically and economically viable and pilot tests and life cycle assessment (LCA) ought to be employed in order to substantiate the performance and environmental advantages. The effective dust extraction system, mandatory respiratory protection, constant monitoring of the exposures, and regular medical surveillance programs should be used to strengthen occupational health protections. Lastly, there is need to have supportive regulatory frameworks, financial incentives, shared processing plants and specifically designed programs of technical assistance that will enable small and medium sized mills to implement cleaner technologies without necessarily undergoing disproportionate economic pressure.

12. Conclusion

Plywood industry lies at a special spot where natural resources are used and industries are manufactured, both of which pose serious environmental threats and viable sustainability possibilities. On the one hand, the process of production results in significant amounts of solid residues, chemically complex wastewater and air emissions that should be properly controlled to avoid the ecological degradation and threats to human health. Environmental stewardship is thus an area that necessitates a complete approach that incorporates the reduction of the source of the material, effective recovery of the material, and treatment systems that are sound technologically. Veneer recovery should be improved, adhesive losses should be reduced, and closed-loop water systems should be used to ensure that the number of waste generated at the source is reduced significantly. Meanwhile, the residue valorization, i. e. turning wood waste into bioenergy or secondary products, will turn the otherwise burdens of disposition into economic and environmental values.

Conversely, plywood still has the benefits of climate-related nature because of renewable raw materials base and biogenic carbon storage ability. Such advantages can be maintained and enhanced whereby adhesive formulas are streamlined to mitigate emissions, energy utilization undergoes transition to biomass or renewable energy, and trash streams are coordinated in the framework of the circular economy. The policymakers as well as the industry stakeholders need to adopt a combination of integrated strategies consisting of technological innovation, enabling regulatory incentives, capacity-building opportunities, and robust occupational health provisions. This is through matching the environmental performance and the economic viability where the sector will limit its environmental footprint and still be able to deliver jobs, infrastructure resources and value added forest products.

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