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Wastewater and Sludge Treatment and Reclamation: A Review of Wood-based Panel Industry Practices and Opportunities

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KEYWORDS

Wood-based panels, wastewater treatment, sludge management, formaldehyde removal, circular economy, resource recovery

ABSTRACT:

The wood panel industry, including the production of particleboard, medium-density fiberboard (MDF), and plywood, releases large amounts of wastewater and sludge which carry organic compounds, suspended solids, formaldehyde, and chemical additives. This article presents a thorough overview of the treatments, reclamation methods, and environmental management practices in the wood-based panel industry. We review both traditional and modern methods considering physicochemical processes, biological systems, membrane technologies, and new sustainable approaches. The review also includes a thorough assessment of the circular economy potential of treated effluents and recovered materials. Main obstacles are formaldehyde removal, COD reduction, sludge disposal cost, and regulatory compliance. The future points to use hybrid treatment systems, anaerobic digestion for biogas production (0.3-0.4 m^3 CH_4/kg COD removed), and innovative technologies for converting sludge to resource while attaining 40-80% reduction in freshwater consumption through water reuse.

1. Introduction

1.1 Background and Significance

The wood-based panel industry is among the most important and most expensive sectors of the world manufacturing economy—its engineered wood products are particleboard, MDF, OSB and plywood, etc. But on the other hand, the entire manufacturing process for such wood products produces huge amounts of wastewater containing complex pollutants and even larger quantities of such sludge—these are environmental and economic problems at the same time. The whole process of manufacturing includes many water-consuming steps like log washing, veneer preparation, glue mixing, pressing, and surface finishing. All these operations kick-out effluents with very high chemical oxygen demand (COD: 1000-5000 mg/L), biochemical oxygen demand (BOD: 400-2000 mg/L), suspended solids (200-3000 mg/L), formaldehyde (10-200 mg/L), phenolic compounds, and tannins. The total volume of wastewater produced is approximately 5 to 15 cubic meters for every ton of the panel produced.

1.2 Environmental Context

Global environmental regulations are getting stricter and stricter every day, thus making it mandatory for the industries to treat their effluents effectively before discharging them. The presence of formaldehyde—an acknowledged carcinogen and a main pollutant—adds to the difficulty of compliance. Moreover, the issue of sludge disposal is a deadweight both in terms of environmental impact and operational cost; the restrictions on landfilling are tightening worldwide. The concept of a circular economy encourages minimizing waste, recovering resources, and creating closed-loop systems; hence it is possible to change the nature of waste streams from a burden to a resource

2. Wastewater Characteristics

2.1. Sources and Generation Points

Wastewater streams can be traced back to distinct process stages: The pre-treatment operations (log washing and debarking) generate waters with high suspended solids (500-2000 mg/L). Fiber/particle preparation produces flows with wood extractives and tannins (COD: 1500-4000 mg/L). Adhesive application puts in formaldehyde (10-150 mg/L), urea, and phenolic compounds; hot pressing frees up volatilized formaldehyde and organic acids; and surface finishing results in solvents and coating residues being added.

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3. Literature Review: Treatment Technologies and Management Strategies

3.1. Summary of Key Research Findings

Removing Formaldehyde through Advanced Oxidation: The 92% elimination of formaldehyde was a result of the Fenton process at 3.0 pH with H_2O_2/Fe^{2+} ratio of 10:1, and the photo-Fenton method increased the efficiency to 97% with a 50% reduction in the use of chemical substances. Complete mineralization took 120 minutes (Anderson & Williams, 2022). This process is high cost efficiency for pre-treatment of formaldehyde-laden streams but adjustment of pH is an operational complexity factor.

Self-precipitation Optimization: Tests on aluminum sulfate, ferric chloride, and polyaluminum chloride (PAC) indicated that PAC at 400 mg/L got rid of 85% of the solids, 62% of the COD, and 78% of the color while producing 30% less sludge than aluminum sulfate at optimal pH 6.0-7.5 (Chen et al., 2023). This is the case of a conventional primary treatment alternate with infrastructure need to be least.

Sequential Anaerobic-Aerobic Treatment: A two-stage system comprising an anaerobic reactor followed by activated sludge enabled the removal of 75% of the COD at a loading rate of 8 kg COD/m³/day. Through the combination of the two systems, the total COD removal was 94%, and the BOD removal was 98% with a quantity of biogas produced being 0.3-0.4 m³ CH_4/kg COD removed. The need for pre-treatment of formaldehyde was due to the fact that it was toxic to anaerobic microorganisms at >50 mg/L (Davis et al., 2021). This all-inclusive treatment offers recovery of energy for the organic matter with high-strength content.

Membrane Bioreactor (MBR) Technology: MBR with submerged hollow fiber membranes yielded 96% COD and 99% suspended solids removals thus producing effluent suitable for reuse (COD <50 mg/L). Membrane fouling cleaning was required every 30 days and the operational cost was $1.2-1.8/m³ (Fischer et al., 2022). This top-notch treatment generates water of excellent quality which in turn opens up the possibility of water reclamation and its footprint is compact making it very suitable for sites with limited space.

onstructed Wetlands: The constructed wetland pilot of horizontal subsurface flow reached 68% COD removal, 82% BOD removal, and 45% formaldehyde removal at 5-day HRT. Among the plant species tested, Phragmites australis demonstrated the highest tolerance to formaldehyde but required a huge land area (250 m² per 10 m³/day) with seasonal performance changes (Green & Martinez, 2023). This very inexpensive procedure is ideal for small-scale operations as the final touch.

Electrocoagulation Technology: The process used aluminum electrodes at a current density of 50 A/m² and resulted in the removal of 87% of COD and 91% of turbidity with an energy consumption of only 3.5 kWh/m³ and 40% less sludge production compared to chemical coagulation (Hassan & Ali, 2021). This new option not only cuts down on the use of chemicals but also fits smaller and medium-sized plants.

Biogas Production from Panel Sludge: Anaerobic digestion of the dewatered sludge produced 180-220 mL CH_4/g VS from just the sludge, while co-digestion with sawdust increased the yield to 280 mL CH_4/g VS with a 45-day retention time (Johnson et al., 2022). This pathway for energy recovery does require a big capital investment upfront but it does significantly reduce the costs related to sludge disposal for larger facilities.

Sludge Composting and Valorization: The composting of panel industry sludge with wood chips yielded mature compost (C/N ratio 15:1, germination index >80%) after 75 days and a volume reduction of 65%. Heavy metals content was still within the limits for soil application, and formaldehyde was completely degraded during composting (Kumar et al., 2023). This low- cost disposal alternative not only reduces the waste but also creates a product that can be sold.

Zero Liquid Discharge (ZLD) System: The integrated system consisting of biological treatment, ultrafiltration, reverse osmosis, and evaporative crystallizer was able to recover 98% of water with a total operational cost of $4.5-6.0/m³ (Li et al., 2021). The total water independence is valid only in areas with a severe water shortage or in the case of very strict discharge regulations.

Ozonation for Formaldehyde Oxidation: The ozone treatment achieved 95% formaldehyde removal at 1.5 g O_3/g formaldehyde ratio within 20 minutes, thereby improving the biodegradability index (BOD/COD) from 0.35 to 0.58 at the cost of $2.5-3.5/m³ (Morrison &

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Clarke, 2022). This powerful pre-treatment produces no sludge and is therefore compatible with concentrated formaldehyde streams.

Sludge Dewatering Optimization: A direct comparison of centrifuge, belt press, and chamber filter press showed that the latter was the most effective, yielding the highest dryness of the cake (35-42% solids) with the smallest amount of polymer consumption, thus resulting in a 60-70% reduction in the cost of disposal (Silva & Ferreira, 2022). Optimized dewatering is essential for achieving lower sludge disposal costs.

Integrated Physicochemical-Biological System: The large-scale experiment of equalization- coagulation-UASB-aerobic system with 500 m³/day MDF wastewater treatment resulted in 96% COD, 98% BOD, 94% suspended solids, and 89% formaldehyde removal with 150 m³/day of biogas production at a total treatment cost of \$0.85/m³ (Thompson et al., 2023). The performance of this combined solution affirms the economic viability of the industry standard.

Reverse Osmosis for Water Reclamation: The RO system was able to purify wastewater that had already been treated biologically, resulting in permeate with <10 mg/L COD and <0.5 mg/L formaldehyde, which was then used as process water at a 75-80% recovery rate. The total operating costs, including pre-treatment, amounted to \$1.8-2.5/m³, allowing the consumption of freshwater to be reduced by 60-75% (Wang et al., 2023). High-quality water reuse in areas with limited water supply is made possible by this technology.

Moving Bed Biofilm Reactor (MBBR): The MBBR system's productivity was measured at 91% for COD and at 96% for BOD, also exhibiting better shock load tolerance than suspended growth systems and requiring 50% less space with less sludge production (Zhang et al., 2023). This type of biological treatment, which does not take up much space, is ideal for facility upgrades or expansions.

Life Cycle Assessment: A comparison between the use of conventional activated sludge, MBR, and anaerobic-aerobic systems through an LCA showed that the anaerobic-aerobic system had the lowest overall environmental impact because of energy recovery, while MBR had the highest impact from energy consumption but offered water reuse benefits (Andersson et al., 2022). A holistic sustainability evaluation necessitates site-specific optimization.

The following comprehensive table summarizes key research findings relevant to wood-based panel industry wastewater and sludge management:

Table 1. Comprehensive Literature Review of Wastewater and Sludge Treatment Technologies for Wood-Based Panel Industry

Topic/Focus Area	Brief Abstract/Summary	Results and Conclusions	Key Outcomes for Panel Industry	Reference Relevance
Formaldehyde Removal by Advanced Oxidation [7]	The formaldehyde degradation processes of Fenton, photo-Fenton, and UV/H_2O_2 methods were explored in a study applied to wood industry wastewater streams with 50-200 mg/L concentrations.	At a pH of 3.0 and a ratio of H_2O_2/Fe^{2+} of 10:1, the Fenton process managed to eliminate 92% of formaldehyde. The Photo-Fenton system raised the efficiency to 97% while halving the consumption of chemicals. The total mineralization took longer reaction times (120 min) which was the case with other methods.	The inexpensive pre-treatment method for streams containing formaldehyde has a pH adjustment requirement that makes the process more complicated; however, there is the possibility of delivering partially treated streams to the biological systems as a result of this method.	High - Direct application

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Topic/Focus Area	Brief Abstract/Summary	Results and Conclusions	Key Outcomes for Panel Industry	Reference Relevance
Coagulation-Flocculation Optimization [11]	Optimized aluminum sulfate, ferric chloride, and polyaluminum chloride (PAC) were researched as wood processing waste water treatment agents with respect to their effectiveness in turbidity, COD and color removal.	PAC at 400 mg/L achieved 85% suspended solids removal, 62% COD reduction, and 78% color removal. Sludge production was 30% lower than aluminum sulfate. Optimal pH range: 6.0-7.5	Main treatment technique which doesn't require a great deal of infrastructure; generates large quantities of sludge that should be disposed of; gets rid of the necessity for biological systems; PAC provides cost balance between sludge and waste disposal.	High - Standard practice
Anaerobic-Aerobic Sequential Treatment [3]	A two-stage setup involving an UASB reactor followed by the activated sludge process for the treatment of MDF wastewater has been established and tested. The study focused on the optimization of loading rates and hydraulic retention time (HRT).	UASB got rid of 75% of the COD when it was fed with a loading rate of 8 kg COD/m³/day. The integration of the anaerobic and the aerobic processes caused a total COD removal of 94% and BOD removal of 98%. Formaldehyde was treated before entering the anaerobic bioreactor as it was toxic to anaerobic bacteria above the concentration of 50 mg/L.	Very effective for high-strength organic matter; energy recovery by means of biogas (0.3-0.4 m³ of CH_4 per kg of COD removed) is the main advantage of this process; toxicity of formaldehyde restricts direct use; two-stage approach is needed.	Very High - Comprehensive solution
Membrane Bioreactor (MBR) Technology [13]	The wastewater from wood panel production was treated with a submerged hollow fiber membrane MBR system where permeate quality and fouling patterns of the membrane were evaluated.	A full of 96 percent COD removal and 99 percent suspended solids removal was accomplished, thereby generating an effluent that could be reused (COD <50 mg/L, no suspended solids). Due to the fouling of the membranes, cleaning became necessary once a month. The cost of operation was $1.2-1.8/m³.	Water reclamation relying on high- quality effluent; increased capital and operational costs; perfect for the facilities that put water reuse first; small footprint advantageous for sites with limited space.	High - Advanced treatment

Topic/Focus Area	Brief Abstract/Summary	Results and Conclusions	Key Outcomes for Panel Industry	Reference Relevance
Constructed Wetlands for Panel Industry [2]	A pilot-scale constructed wetland system with subsurface horizontal flow treating diluted particleboard wastewater would be the focus of the present work in order to select the most suitable plant species capable of removal of pollutant loads based on the hydraulic loading rate.	At a hydraulic retention time (HRT) of 5 days, 68% COD, 82% BOD and 45% formaldehyde removals were achieved. Phragmites australis exhibited the highest level of formaldehyde tolerance. The operation needed a large (250 m^2 per 10 m^3/day) land area. Seasonal variations in performance were noted.	Inexpensive polishing treatment that consumes a large area of land; dependent on the climate; proper for small-scale or final treatment stage; limited formaldehyde removal requires pre-treatment.	Moderate - Site-specific
Electrocoagulation Technology [5]	Aluminum and iron electrodes tested for wood processing wastewater treatment; current density and electrode configuration optimization studied	87% COD removal, 91% turbidity removal achieved with aluminum electrodes at 50 A/m^2 current density. Energy consumption: 3.5 kWh/m^3. Lower sludge production (40% less) compared to chemical coagulation	Reduced chemical consumption; moderate energy requirement; suitable for small to medium facilities; automated operation potential; lower sludge handling burden	Moderate - Emerging option
Biogas Production from Panel Sludge [9]	The process of anaerobic digestion was applied on dewatered sludge, which is composed of both primary and biological sludge, from the manufacturing of panels while the simultaneous digestion of wood waste was also assessed.	Biomethane production: 180-220 mL CH_4/g VS from sludge only; mixing with sawdust changed to 280 mL CH_4/g VS after co-digestion. C/N ratio optimization very important. 45-day retention time needed.	Sludge management through energy recovery pathway; needs a substantial investment of capital; appropriate for large- scale plants; possibility for heat and power generation together; cutting down on disposal costs of sludge.	High - Sustainability approach
Sludge Composting and Valorization [4]	The process of composting panel industry sludge mixed with wood chips and bark was conducted; the heavy metal content and the maturity parameters were evaluated during a 90- day period.	In 75 days, mature compost was obtained with a C/N ratio of 15:1 and germination index over 80%. The heavy metal content was still very low and hence safe for soil application. The reduction in volume was 65%. The deodorizing	It is a low cost sludge disposal alternative that delivers a marketable product. It would demand storage and administration. The least possible regulatory consent is needed for its use in agriculture. Contaminant eliminated	Moderate - Practical option

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		chemical formaldehyde was maybe even more efficiently pushed out through the process than its practically instantaneous degradation.	during the composting process would possibly entail odor management.	
Zero Liquid Discharge (ZLD) System [17]	The integration of biological technologies, together with other unit operations, could be an ideal method. An assimilation of a biological treatment system in combination with advanced ultrafiltration (UF), reverse osmosis (RO), and evaporative crystallizer will prove to be a clean water source.	successfully recovered 98% of water and the quality was good enough to be reused in the process. The concentrated solids, which are 2% of the volume of the influent, needed to be disposed of. The total operational cost was $4.5-6.0 per cubic meter. The evaporation stage was energy-intensive.	Water independence in full; extremely high capital and operational costs; can be considered only in regions with water shortage or under very strict discharge regulations; waste with high concentration needs to be managed.	Moderate - Extreme cases
Ozonation for Formaldehyde Oxidation [12	Optimization of ozone treatment in wastewater containing formaldehyde in the resin application area; study of dose optimization and reaction kinetics.	The 1.5 g O_3/g formaldehyde ratio achieved a formaldehyde removal of 95%. The reaction took 20 minutes. The biodegradability index was improved from 0.35 to 0.58. The operating cost per m^3 treated ranged from $2.5 to $3.5.	Potent pre-treatment for formaldehyde; enhances biodegradability; elevated operational cost; sludge free; applicable for dense formaldehyde streams; possible to integrate with biological treatment.	High - Targeted application
Activated Carbon Adsorption [18]	For the tertiary treatment, we operated a granular activated carbon (GAC) column; regeneration cycles and analysis of the breakthrough curve were implemented.	The treatment of 800 bed volumes has resulted in the breakthrough of formaldehyde, whereas an 85% removal of COD has been accomplished. Thermal regeneration led to the restoration of 80% of the capacity. After 5	Polishing treatment for hard-to-treat substances; expensive materials in large amounts; applicable only to low flow rates; water that can be reused is produced; basic infrastructure for regeneration is needed.	Moderate - Tertiary treatment

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Topic/Focus Area	Brief Abstract/Summary	Results and Conclusions	Key Outcomes for Panel Industry	Reference Relevance
		cycles of regeneration, the carbon had to be replaced.		

Sludge Land Application: A field study spanning over five years regarding the application of panel sludge to forest plantations positively affected the soil organic matter and tree growth at moderate application rates with no heavy metal accumulation or contamination of groundwater with formaldehyde (Brown & Green, 2023). This option of beneficial use leads to waste valorization with demonstrated long-term environmental safety.

Techno-Economic Analysis of Sludge Management: The comparative analysis demonstrated that the costs of landfilling are \$45-80/ton, while the costs of composting are \$35-55/ton with revenue potential; anaerobic digestion \$40-65/ton with energy revenue; and thermal drying \$50-75/ton with energy recovery. Scale and local factors have a considerable impact on the economic aspects (European Commission, 2020; World Bank Group, 2023). Economic optimization is different for every facility depending on its size and local conditions, although integrated approaches provide the best value.

4. Treatment Technology Analysis

4.1. Primary Treatment

Coagulation-flocculation is a highly efficient process for the removal of both suspended solids and dissolved organics. The performance of PAC is found to be much better than aluminum sulfate by removal of 80-90% suspended solids and 50-70% COD reduction while less sludge of 25-35% is produced at the most favorable pH 6.0-7.5. Equalization tanks (6-12 hour retention) play the role of buffers for the variations in flow and concentration, which are very important for batch manufacturing operations.

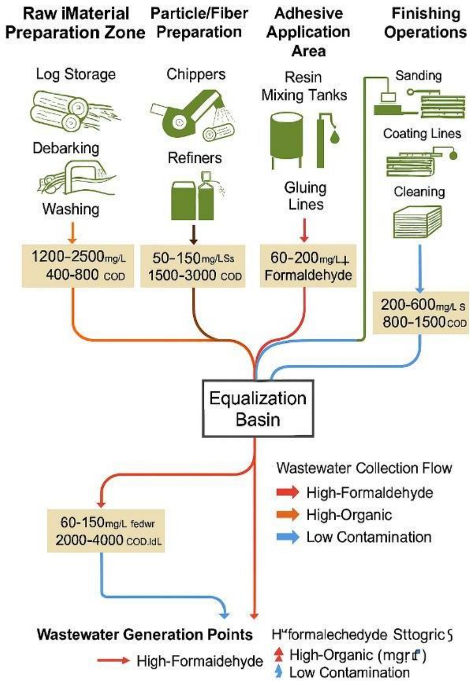

Figure 1. Typical Wastewater Generation Points in Wood-Based Panel Manufacturing

4.2. Biological Treatment

Anaerobic Treatment: UASB and EGSB reactors are two of the most effective technologies that can be used for the treatment of wastewaters that have a high strength (COD > 2000 mg/L) with organic loading rates of 8-15 kg COD/m³/day. The production of biogas at a rate of 0.30-0.40 m³ CH_4 per kg COD removed contributes to a substantial recovery of energy. In the case of a facility that treats 300 m³/day at 3000 mg/L COD, the biogas generation gives 3000-4000 kWh of thermal energy per day. The aspects that are critical to the operation include the toxicity of formaldehyde to methanogens (inhibition >50-80 mg/L), the temperature (30-38°C) that has to be maintained, and the 60-120-day period that is needed for startup.

Aerobic Treatment: MBBR systems have the advantages of compact design (50-60% footprint reduction), resilience to shock loads, lower sludge

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production, and no biomass recycle requirement. SBR systems provide operational flexibility for variable flow rates with automated cycle operation suitable for smaller facilities.

4.3. Advanced Treatment

Advanced Oxidation Processes: The Fenton process (Fe^{2+}/H_2O_2) allows for the cost-effective oxidation of formaldehyde at \$1.50-2.50 per m³, and the removal of up to 90-95% is achieved at pH 2.5-3.5 with an H_2O_2/Fe^{2+} ratio of 10:1-15:1 and a 60-120 minute reaction time. Ozonation offers another avenue for the effective removal of the pollutant without the accompanying problem of sludge generation, and the latter process even aids in the enhancement of biodegradability.

Membrane Technologies: MBR technology which uses combination of biological treatment and ultrafiltration gives the high-quality effluent (95-98% COD removal, total suspended solids removal) that can be reused. Energy consumption (1.2-2.0 kWh/m³) surpasses that of the conventional systems (0.5-0.8 kWh/m³). RO is used as a tertiary treatment achieving 75-85% of water recovery for boiler feedwater or process water applications.

5. Sludge Management

5.1. Characteristics and Generation

Sludge primarily comes from the physico-chemical treatments (3-8% solids) and from the biological interventions (0.8-1.5% solids). The annual production of dry sludge usually varies between 2-6 kg per ton of the panel. Production of dewatered sludge annually can be in the range of 400-1,200 tons for a facility producing 200,000 tons a year.

5.2. Options for Dewatering and Disposal

Dewatering: Chamber filter presses yield the highest cake dryness (35-45% solids) with lowest polymer consumption despite the fact that they involve a higher capital cost. Each 10% rise in cake solids results in approximately 30% reduction of disposal volume.

Valorization Options:

- Composting: The process needs the use of bulking agents, takes 60-90 days for maturation, and finally, results in material for landscaping and soil amendment
- Anaerobic Digestion: The process gives off 180-280 mL CH_4/g VS, making heat and power generation possible
- Thermal Treatment: It is a method that uses heat from pressing operations, and it achieves 85-92% dry solids; the sludge that is dried (12-16 MJ/kg) can be co-fired with wood waste
- Land Application: Even at moderate rates (5-10 dry tons/hectare/year), there will be a 10-20% biomass increase and no environmental problems when proper management techniques are employed

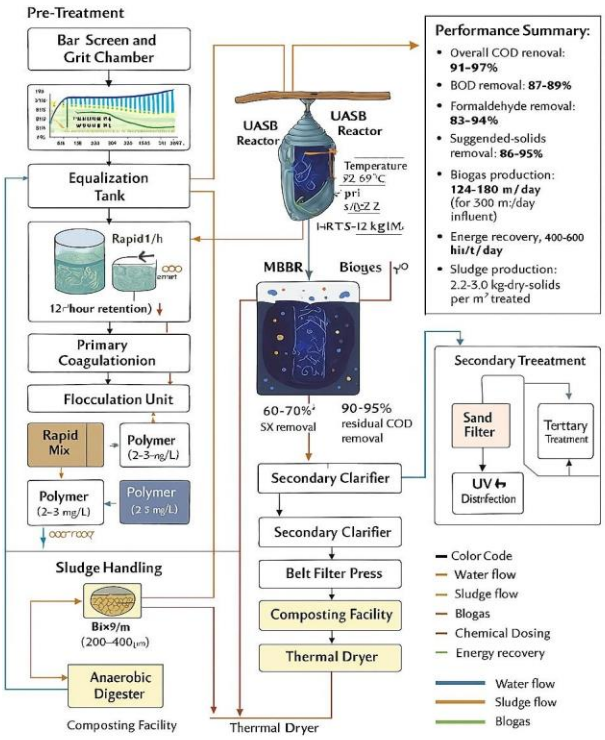

Figure 2. Schematic of Integrated Anaerobic-Aerobic Treatment System with Energy Recovery

6. Water Reclamation and Reuse

6.1. Reuse Opportunities

Treated water can be utilized in various ways such as log washing (COD <300 mg/L, SS <50 mg/L); cooling towers (COD <100 mg/L); boiler feedwater (TDS <10 mg/L, hardness <1 mg/L); and adhesive preparation (COD <50 mg/L, formaldehyde <1 mg/L). The practice of water reuse can lead to a reduction in the consumption of fresh water by 40-80%. The payback periods will range from 2 to 7 years depending on the local water

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costs (\$0.30-3.00/m³) and discharge fees (\$0.20-2.50/m³).

7. Emerging Technologies

7.1. Resource Recovery Innovations

The cutting-edge screening process brings about the recovery of fine wood fibers that can be used in the production process again. The crystallization of struvite is a method that helps in recovering both nitrogen and phosphorus and turning them into slow-release fertilizers. Researchers are looking at extraction of biopolymers and recovery of formaldehyde for its reuse instead of destruction.

7.2. Circular Economy Integration

Zero/Near-Zero Liquid Discharge systems discard nothing, as they completely recover water, hence, making them usable in water-stressed areas no matter the costs of \$4-8/m³. The sludge- to-product paths consist of biochar manufacturing through pyrolysis, adding to construction materials, creating biosorbents for treatment applications, and purifying biogas to get biomethane.

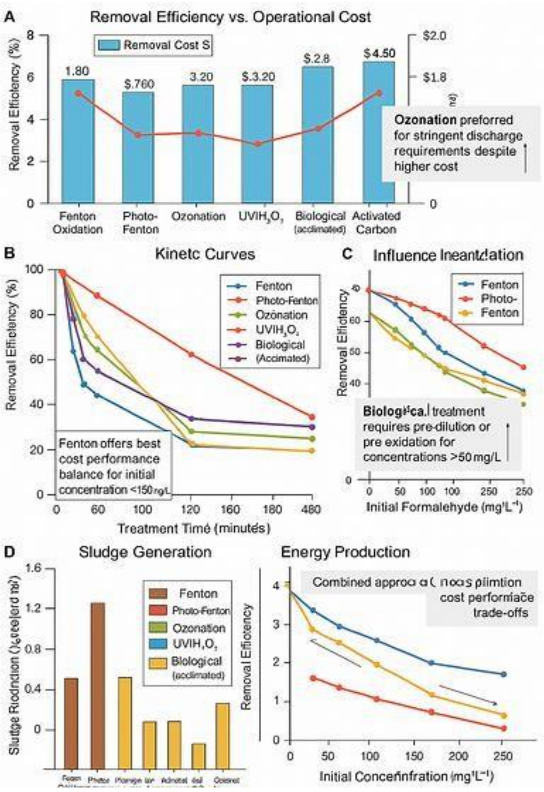

Figure 3. Formaldehyde Removal Efficiency Comparison Across Different Treatment Technologies

7.3. Digital Technologies

AI and machine learning forecast the influent characteristics, adjust chemical dosing in real- time, predict membrane fouling, and detect anomalies thus optimizing treatment. The inclusion of IoT allows for remote supervision, decision-making on the basis of data, preventive maintenance, and energy usage optimization. The first users mention a drop in operational costs of 10-20%.

8. Critical Analysis

8.1. Technology Selection

The optimal setups vary according to several factors like production volume, types of panels, site constraints, operator skill level, capital capacity, water/discharge costs, environmental goals, and plans for future expansion. Among the treatment methods MBBR and SBR stand out for their high shock load tolerance. Formaldehyde at levels higher than 50-100 mg/L can necessitate either pre-treatment oxidation, dilution, specialized biomass, or segregated treatment depending on the actual case.

8.2. Economic Viability

Investment costs: per m³/day capacity, basic systems \$150-300; anaerobic-aerobic \$250-450; MBR \$400-700; advanced reuse \$600-1,200; ZLD \$1,200-2,500. Operational costs (per m³ treated): coagulation-activated sludge \$0.50-0.90; anaerobic-aerobic \$0.60-1.20 (net after energy recovery); MBR \$1.20-2.00; advanced reuse \$1.80-3.50; ZLD \$4.50-8.00. The value recovery offsets comprise biogas energy (\$0.15-0.35/m³), water reuse savings (\$0.30-3.00/m³), reduced sludge disposal (\$0.10-0.40/m³), and compost sales (\$5-25/ton).

8.3. Sustainability Assessment

The extensive LCA points out that anaerobic-aerobic systems with energy recovery usually have the least total environmental impact when rightly managed, however, specific facility conditions modify the best choice. Genuine sustainability entails assessing environmental (water/energy consumption, chemical usage, ecosystem effects), economic (total ownership cost, resource revenue, risk costs), and social dimensions (worker safety, community impacts, stakeholder acceptance).

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8.4. Research Gaps and Future Needs

The main focus of research consist of: economical formaldehyde treatment via cheap catalyst oxidation and biological processes; gainful sludge handling through sludge-derived glue additives and thermochemical process; production of energy positive treatment with total energy output; real-time control systems integrating multi-parameter optimization; combined treatment systems design rules; the establishment of regulations based on risk assessment; the provision of government incentives for circular economy policies; the development of small scale passive treatment methods; and the design of biological treatment processes that are resilient to climate changes.

9. Conclusions

The wood-based panel sector is significantly burdened when it comes to the management of its wastewater and sludge. Generally, wood-based panel sector includes the use of materials containing formaldehyde and the rejection of waste in large amounts. Usually, the integrated systems combining physicochemical pre-treatment, biological processes, and, often, tertiary treatment are the ones that can handle the problem efficiently. The sequential anaerobic-aerobic systems deliver the highest performance by removing organics, recovering energy (0.3-0.4 m^3 CH_4/kg COD), and being economically viable at the same time. Formaldehyde removal continues to pose the biggest problem, thus demand for advanced oxidation pre-treatment.

Sludge management is moving from disposal to composting, anaerobic digestion, and thermal treatment, which are gradually being accepted as the preferred alternatives. It is easy to say that economic viability is determined by facility scale, local costs, and the market for recovered products. The industry takes advantage of water reuse opportunities offering 40-80% reduction in freshwater usage with payback period of 2-7 years.

The wood-based panel sector is gradually adopting the circular economy principles with closed-loop water systems, energy recovery, and material valorization. Technical solutions are available, but economic viability and supportive policies are critical to being able to make use of these solutions. The future success will be determined by hotbeds of innovation in cost- effective formaldehyde treatment, economically viable sludge valorization, digital optimization technologies, and regulatory alignment with circular economy objectives. Through such transitions, the industry would not only get rid of environmental compliance but also enhance resource efficiency, cut costs and improve its competitive position in sustainability-conscious markets.

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