Pollutant Removal in Stormwater by Woodchips

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Abstract

As urbanization continues, water pollution is of increasing concern for human health and the environment. Water contaminants common in urban stormwater include nutrients, metals, suspended solids, pesticides, and pathogens. The search for an inexpensive and readily available material that can effectively remove common stormwater contaminants is ongoing. Studies have shown that woodchips are a promising material that can remove many different contaminants, including these common contaminants and emerging contaminants of concern. The type of wood and shape of woodchips can impact the removal efficiencies of different contaminants due to different partitioning coefficients and capillary action. This review compiles studies on the ability of woodchips of different types to remove these common stormwater contaminants and emerging contaminants of concern. Overall, the literature demonstrated woodchips are an inexpensive and effective material that could be implemented for the removal of contaminants in urban stormwater.

Keywords: Water contaminants; Woodchips; Biological degradation; Pollutants; Aquatic organisms; Environment

Introduction

In an ever-urbanizing society, water pollution is becoming more of a concern for human health and the health of the environment. There are many water contaminants associated with urbanization including nutrients, heavy metals, eroded sediment, hydrocarbons, and pathogens. As water pollution continues to increase, the search for inexpensive, readily available, and effective treatment techniques for remediating pollution in runoff is increasingly important. Woodchips have been investigated as an inexpensive treatment medium for many types of pollutants. Woodchips remove these pollutants by utilizing processes such as filtration, sorption, and biological degradation, and performance can be influenced by wood properties such as type of wood and shape. This review summarizes a variety of studies that demonstrate the use of woodchips for effectively removing a variety of pollutants. Utilizing this readily available material for pollutant removal from stormwater runoff could provide a low-cost, sustainable solution for water-quality improvement in stormwater runoff across the globe.

Pollutant Removal

Common stormwater contaminants vary in chemical properties, resulting in different impacts on human health and the environment and different removal processes. Sorption is one process woodchips utilize to remove pollutants. Woodchips are a porous material, so they contain small capillaries where water can flow by capillary action [1]. As the water flows through the capillaries, pollutants sorb to the woodchips and are removed from the water. Woodchips also remove some pollutants through physical processes, such as filtration, where woodchips intercept the flow of water, allowing suspended contaminants to stick to the woodchips and be removed from the water [2]. Retention of pathogens in the woodchips can expedite deactivation of pathogens through natural decay, desiccation, or predation [3]. Ion exchange can also occur when cations replace phenolic hydroxyl groups, found in the tannins in woodchips [4]. Another process woodchips utilize to remove pollutants is biological degradation, which can occur in toxic or anoxic conditions. Most organic matter is degraded through oxidation by aerobic bacteria. The oxygen that is required for degradation of the organic material present in the water is represented by BOD or COD, so as organic matter is degraded, BOD and COD will decrease. Denitrification occurs in anoxic zones with low ventilation efficiency, such as the pores of woodchips or saturated zones [5]. Denitrifying bacteria use woodchips as a carbon source and nitrates as a terminal electron acceptor,
resulting in the conversion of nitrates to nitrogen gas [5].

Water quality indicators

Water quality indicators include biological oxygen demand (BOD), chemical oxygen demand (COD), and suspended solids and are indicative of poor water quality that may be caused by pollutants such as excess nutrients, oils and grease, and/or sediment. BOD and COD are indicative of organic material in the water, and suspended solids can have other pollutants adsorbed to them, so their removal is imperative. BOD and COD are removed by biological degradation, and suspended solids are removed through physical filtration by woodchips [6-10].

Nutrients

Excess nutrients in water can cause issues, such as eutrophication. Many studies have found that woodchips remove nutrients from water, including nitrate, sulphate, ammonia, ammonium, nitrite, orthophosphorus, and particulate phosphorus [2,3,5,6,9,11-17]. Nutrients vary in their chemical properties, so their removal processes vary as well. Woodchips act as the carbon source in the biological degradation of nitrate, sulphate, ammonia, ammonium, and nitrite [5,13]. Particulate phosphorus is phosphorus adsorbed to suspended sediment, so it is removed by physical filtration along with suspended solids [2]. Orthophosphorus, is removed through sorption, and nitrates can be removed by sorption as well as biological degradation [14].

Heavy metals

Heavy metals can be toxic to humans and aquatic organisms, and their presence can disrupt aquatic ecosystems. Mulch and woodchips have proven effective for heavy metal removal, but some metals, such as arsenic, have not been studied [4,13,18-21]. Metals are removed through sorption to the woodchips and cation exchange with phenolic hydroxyl groups. The composition of the wood can greatly affect the removal efficiency of the metals [4].

Pesticides

Pesticides often persist long term in the environment and are detrimental to human health and the environment. Many pesticides are organochlorides, which interact with the organic material in the woodchips through sorption [22] or physical filtration of sediment on which pesticides are sorbed [23]. Several studies have found woodchips to effectively remove pesticides [15,21,22,24,25].

Total petroleum hydrocarbons

Total petroleum hydrocarbons describe a broad family of chemical compounds associated with crude oil, including aliphatic hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and monocyclic aromatic hydrocarbons (MAHs) (ASTDR, 1999). They have shown to be effectively removed by wood products in many studies, by sorption to the woodchips as well as physical filtration of sediments to which hydrocarbons are sorbed and biological degradation [19,24,26-29].

Other halocarbons

Other halocarbons have similar characteristics to pesticides and have also been found to be removed by wood through sorption. The other halocarbons studies include surfactants [28], fluorene [27], 1,3-Dichlorobenzene, butylbenzylphthalate, fluoranthene [19], trichloroethene [30], 1,2-Dichlorobenzene, 1,3,5-Trichlorobenzene, and chlorobenzene [24].

Pathogens

Pathogens present a risk to the health of humans and aquatic organisms and are often indicative of fecal material in water. There is a limited amount of research evaluating the ability of wood to remove water-borne pathogens. Soupir et al. [3] evaluated the removal of E. coli and Salmonella, and Rambags et al. [31] evaluated the removal of E. coli and F-specific RNA bacteriophage, an indicator of viral pollution, by wood products, both finding effective removal of these pathogens. Pathogens are removed by sorption to woodchips or physical filtration if they are adsorbed to sediments in the inflow, causing the deactivation of pathogens by natural decay, desiccation, or predation [3].

Other emerging contaminants

Other pollutants that wood mulch can treat include explosives such as Trinitrotoluene (TNT), Rapid Detonating Explosive (RDX), and octogen (HMX) [32]; and emerging contaminants [33]. The chemical structures and properties and environmental impact of these contaminants vary greatly, but they all have potential of being removed by wood products. Less is known about the interactions of these chemicals with woodchips, but many emerging contaminants are likely removed by sorption (Table 1).

Effect of Woodchip Shape and Type

Woodchips are broadly effective for the removal of common stormwater contaminants, but their effectiveness can be impacted by both shape and type. The shape of the woodchips affects the way water flows through the pore spaces in the woodchips, which can affect sorption, ion exchange capacity, and even biological degradation. Additionally, different types of wood have different chemical compositions, which can lead to different sorption and ion exchange abilities.

Shape of woodchips

Wood’s sorption and ion exchange capacity are impacted by capillary flow, which is the movement of liquid by capillary action. Washburn [34] defined capillary action for straight cylindrical tubing as,

$$ l = \frac{\gamma \cos(\theta)}{4\eta}t = Kt $$  \hspace{1cm} (1)

where l is the length the fluid traveled, γ is the surface tension, D is the tube diameter, t is time, θ is the contact angle, η is the dynamic viscosity, and K is referred to as the Washburn slope. The
Washburn equation, that assumes straight capillary tubes, can be adapted for use in porous media that have tortuous connecting pores. In fibrous materials, such as woodchips, the pore spaces are irregular. This can cause variations in the effective pore diameter and contact angle. Wålinder & Gardner [35] examine the factors influencing effective pore radius and contact angle in spruce chips with several different wetting fluids. They used fluids that have low surface tensions, methanol and hexane, with an effective contact angle of zero. From those experiments, the effective pore diameter for the spruce chips was found [36].

**Table 1**: Literature summary of pollutant removal from water by wood mulch. TPH = Total Petroleum Hydrocarbons, PAH = Polycyclic Aromatic Hydrocarbon, MAH = Monocyclic Aromatic Hydrocarbon, Cd = Cadmium, Cr = chromium, Hg = Mercury, Pb = lead, Mn = Manganese, Cu = Copper, Zn = Zinc, WQ = Water Quality, BOD = Biochemical Oxygen Demand, COD = Chemical Oxygen Demand, SS = Suspended Solids and TSS = Total Suspended Solids.

| Target Pollutant | Wood Type(s) | Research Focus | Reference |
|------------------|--------------|----------------|-----------|
| **WQ Indicators** |              |                |           |
| COD, TSS         | Woodchip and pumice | Constructed wetland | Niu et al [10] |
| BOD, COD, SS     | Multiple types (review paper) | Greywater treatment | Dalahmeh et al. [8] |
| BOD              | Eucalypt wood mulch | Constructed wetland | Saeed and Sun [9] |
| BOD              | Wood mulch     | Biofiltration for compost liquor | Savage and Tyrll [6] |
| BOD, COD, TSS    | Wood mulch     | Greywater treatment | Zuma et al [7] |
| Nitrate          | Hardwood chips | Effect of temperature and retention time | Soupir et al [3] |
| Nitrate, nitrite ammonia | Pine woodchips | Mine water treatment | Nordström and Herbert [17] |
| Particulate phosphorus | Monterey pine woodchips | Woodchip filtration of agricultural runoff | Choudhury et al. [2] |
| Ammonia, nitrate, nitrite, orthophosphorus | Wood chips and fibers | Septic tank leachate | Xuan et al [14] |
| **Nutrients**    |              |                |           |
| Nitrate          | Pine wood mulch and wheat straw | Bioreactors | Camilo et al [15] |
| Nitrate          | Pine bark mulch | Landfill leachate | Frank et al [16] |
| Nitrate          | Softwood branches and bark, hardwood chips and branches, coniferous twigs and leaves, mulch, willow wood chips, compost, and beech leaves | Permeable Reactive Barrier for groundwater | Gibert et al. [12] |
| Nitrate          | Wood chips    | Bioretention for urban runoff | Kim et al [5] |
| Nitrate          | Wood mulch, sawdust, leaf compost | Permeable Reactive Barrier for groundwater | Robertson et al [11] |
| Sulphate         | Eucalypt wood mulch | Constructed wetland | Saeed and Sun [9] |
| Sulphate         | Chipped wood mulch | Bioreactor for mine drainage | Edwards et al [13] |
| **Heavy Metals** |              |                |           |
| Cd, Cu, Ni, Pb, Zn | California redwood, oak, Douglas fir woodchips | Effect of biochar and straw additives | Ashoori et al [21] |
| Cd, Cr(III), Cr(VI), Hg, Pb | Multiple (review paper) | Potentially low-cost sorbents for heavy metals | Bailey et al [4] |
| Mn               | Chipped wood mulch | Bioreactor for mine drainage | Edwards et al [13] |
| Cu, Pb, Zn       | Cypress bark, hardwood bark, pine bark nugget | Urban runoff | Jang et al [18] |
| Cu, Cd, Cr, Pb, Zn | Hardwood mulch | Heavy metal and organic removal | Ray et al. [19] |
| Cu, Zn, Pb       | Packing wood   | Urban runoff   | Seelsaen et al. [20] |
| Pollutant Type | Compounds | Woodchips | Treatment | References |
|---------------|-----------|-----------|-----------|------------|
| Pesticides    | Fipronil, diuron, atrazine, 2,4-D | California redwood, oak, Douglas fir woodchips | Effect of biochar and straw additives | Ashoori et al. [21] |
|               | Heptachlor, aldrin, endrin, dieodrin, DDE, DDT, DDE | Pine bark | Halo carbon pesticide removal | Bras et al. [22] |
|               | Atrazine, bentazone | Pine wood mulch and wheat straw | Bioreactors | Camiko et al. [15] |
|               | Diuron, isoxaben, oryzalin, clopyralid | Shredded cedar mulch | Herbicide removal | Huang et al. [25] |
|               | DDT | Willow branches, oak branches | Wood Sorption Capacity | Trapp et al. [24] |
| PAH (anthracene), MAH (naphthalene and pyrene) | Aspen wood fibers | Wood sorption capacity | Boving & Zhang [27] |
| MAH (benzene, toluene, and o-xylene) | Douglas fir and Ponderosa pine | Wood sorption capacity | MacKay & Gschwend [26] |
| MAH (naphthalene and benzopyrene) | Hardwood mulch (combination of Silver Maple, Norway Maple, Red Oak, and Cherry) | Heavy metal and organics removal | Ray et al. [19] |
| PAH (phenanthrene and pyrene) | Hardwood bark mulch | Biofilm barrier for groundwater | Seo et al. [28] |
| MAH (benzene, phenol, xylene, and naphthalene) | Willow branches, oak branches | Wood sorption capacity | Trapp et al. [24] |
| Fluorene | Aspen wood fibers | Wood Sorption Capacity | Boving and Zhang [27] |
| 1,3-Dichlorobenzene, butylbenzylphthalate, and fluoranthene | Hardwood mulch (combination of Silver Maple, Norway Maple, Red Oak, and Cherry) | Heavy metal and organic removal | Ray et al. [19] |
| Surfactant | Hardwood bark mulch | Biofilm Barrier for groundwater | Seo et al. [28] |
| Trichloroethylene | Shredded tree mulch and cotton gin trash | Permeable Reactive Barrier for groundwater | Shenl et al. [30] |
| 1,2-Dichlorobenzene, 1,3,5-Tri-chlorobenzene, and chlorobenzene | Willow branches, oak branches | Sorption of lipophilic organic compounds | Trapp et al. [24] |
| E. coli, Salmonella | Hardwood chips | Effect of temperature and retention time | Soupir et al. [3] |
| E. coli, F-specific RNA bacteriophage | Monterey pine woodchips | Denitrifying woodchip bioreactor | Rambags et al. [31] |
| Acetaminophen, caffeine, carbamazepine, ibuprofen, sulfathiazole, benzoxtiazole, 5-methyl-1H-benzotriazole | California redwood, oak, Douglas fir woodchips | Emerging contaminant removal | Tseng et al. [33] |
| TNT, RDX, HMX | Pine bark, pine mulch | Permeable reactive barrier for groundwater | Ahmad et al. [32] |
Staples & Shaffer [1] present an equation that was catered to capillary rise in porous media rather than using the Washburn equation that was intended for straight cylindrical tubing. This was done by testing the wetting front of saline in uniform glass bead beds to find the simplistic flow front model,

\[ \ln \left( \frac{l - l_{eq}}{l_{eq}} \right) = \frac{D_{eq} \rho g l_{eq}}{2 \eta g_{eq}} \quad (2) \]

where \( D_{eq} \) is the diameter at the throat that limits viscous drag, \( \rho \) is the fluid density, \( g \) is the gravity constant, \( t \) is the time, and \( l_{eq} \) is the equilibrium length, which is a function of surface tension, contact angle, throat diameter, density, and gravity given by,

\[ l_{eq} = \frac{2 \gamma \cos \theta}{D_{eq} \rho g} \quad (3) \]

where \( D_{eq} \) is the diameter at the largest portion of the tube that limits capillary pressure. More research is needed to determine what shape and size of woodchips would have the highest removal efficiencies.

### Type of wood

Trees can be categorized as either softwoods or hardwoods. Softwoods are coniferous trees that produce their seeds in cones. Examples of softwoods are cedar, redwoods, and pine. Hardwoods are flowering trees that produce their seeds in fruit. Some hardwoods are denser than others and are further separated as soft hardwoods and hard hardwoods. Examples of soft hardwoods include cottonwoods, balsa, and willows. Examples of hard hardwoods include oak, hickory, and mahogany. Softwoods generally have higher amounts of lignin than hardwoods. Lignin contains polyhydric phenols and other functional groups on its surface, making it important in the role of woodchips as a sorbent for metals and hydrocarbons [4]. Bailey et al. [4] found that sorption of metals, such as copper; chromium, zinc, nickel, mercury, and lead on woodchips occurred primarily on the lignin or tannin components (1999). MacKay & Gschwend [26] found that two different softwoods, Douglas fir and Ponderosa pine, had a high equilibrium sorption capacity for benzene, o-xylene, and toluene. They also combined the work of Stamm & Millet [37], Garbarini & Lion [38], Xing et al. [39] and Severtson & Soupir M, Hoover N, Moorman T, Law J, Bearson B (2018) Impact of temperature and hydraulic retention time on pathogen and nutrient removal in woodchip bioreactors. Ecological Engineering 112: 153-157.

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