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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 in the pores of the woodchips, removing them 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, orthophorphorus, 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,

$$l^2 = \frac{\gamma D \cos(\theta)}{4\eta} t = Kt \qquad (1)$$

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 Tyrrl [6]
	BOD, COD, TSS	Wood mulch	Greywater treatment	Zuma et al. [7]
Nutrients	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]
	Ammonia, Ammonium	Wood mulch	Biofiltration for compost liquor	Savage and Tyrrl [6]
	Nitrate	Pine wood mulch and wheat straw	Bioreactors	Camilo et al [15]
		Pine bark mulch	Landfill leachate	Frank et al [16]
		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]
		Wood chips	Bioretention for urban runoff	Kim et al [5]
		Wood mulch, sawdust, leaf compost	Permeable Reactive Barrier for groundwater	Robertson et al [11]
	Sulphate	Eucalypt wood mulch	Constructed wetland	Saeed and Sun [9]
		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]

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, dieldrin, DDD, DDT, DDE	Pine bark	Halocarbon pesticide removal	Bras et al. [22]
	Atrazine, bentazone	Pine wood mulch and wheat straw	Bioreactors	Camilo 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]
TPH	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]
Other Halocarbons	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-Trichlorobenzene, and chlorobenzene	Willow branches, oak branches	Sorption of lipophilic organic compounds	Trapp et al. [24]
Pathogens	*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]
Miscellaneous	Acetaminophen, caffeine, carbamazepine, ibuprofen, sulfathiazole, benzotriazole, 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,

$$\ln\left(l-\frac{l}{l_{eq}}\right)+\frac{l}{l_{eq}}=\frac{D_{vis}^{2}\rho g}{32\eta l_{eq}}t \qquad (2)$$

where D_{vis} is the diameter at the throat that limits viscous drag, ρ 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,

$$l_{eq}=\frac{4\gamma\cos\theta}{D_{cap}\rho g} \qquad (3)$$

where D_{cap} 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 & Banerjee [40] to determine a relationship between the lignin-water partition coefficient of the wood (K_{lignin}) and octanol-water partition coefficient of the chemical (K_{ow}). The additional chemicals include other petroleum hydrocarbons and chlorocarbons such as phenol, trichloroethylene, dichlorophenol, and trichlorophenol. The best fit regression for K_{lignin} and K_{ow} of the data that MacKay & Gschwend [26] compiled is,

$$\log K_{lingin}=0.74(\pm 0.09)\log K_{ow}-0.04(\pm 0.25) \qquad (4)$$

where K_{lignin} is in $(\text{mol}\cdot\text{g}_{\text{lignin}}^{-1})\cdot(\text{mol}\cdot\text{mL}_{\text{water}}^{-1})^{-1}$ and K_{ow} is in $\text{mL}\cdot\text{g}^{-1}$.

Lignin has been found to have a high sorption capacity for hydrocarbons and metals, which makes woods with high lignin content more efficient sorbents.

Conclusion

These studies have shown that woodchips are an effective material for the removal of many different contaminants from water. There are still some unanswered questions in the literature regarding the pollutant removal capabilities of woodchips, including:

a) What is the effect of moisture content on the ability of woodchips to remove contaminants?

b) What is the effect of external factors, such as humidity, solar radiation, and wind speed on the ability of woodchips to remove contaminants?

c) How well can woodchips remove other pollutants, such as arsenic, that have not been previously investigated?

d) What shape and size of woodchips are most effective for pollutant removal?

The literature has shown that woodchips can effectively remove many different contaminants of concern that are commonly found in urban runoff. It is a promising and inexpensive material that could be widely implemented to reduce the transport of contaminants through stormwater.

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