Characterization, toxicity and treatment of wood leachate generated outdoors by the wood-based industry

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Henric Svensson

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Abstract

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Wood is a natural raw material, and would hardly be considered a risk to the environment. However, the handling of wood materials on an industrial scale has been shown to have a negative impact on water bodies that run-off from industrial sites that process wood-based materials. Most investigations related to water pollution from wood-based industries have focused on large industrial sites such as pulp and paper mills. The goal of the present thesis is to understand better such environmental problems and treatment solutions that occur at most wood handling sites. Where there are large outdoor storage areas for logs and sawdust that are exposed to rainfall or irrigation, such as the wooden-floor and bio-energy sectors. Leachate generated by the contact of water with wood in storage areas contains a large amount of organic matter that is potentially hazardous to water bodies that receive run-off from the site.

It has been found that different wood species yield different leachate compositions, with leachate from oak having the highest pollutants content, followed by leachate from pine. This investigation shows that oak has the potential to leach about 10 times the amount of polyphenols compared with other investigated species (i.e., pine, beech and maple). Furthermore, oak leachates have the lowest ratio of biological oxygen demand at 7 days to chemical oxygen demand (0.12), which suggests a potential problem with the biological degradation of this leachate. It has also been shown that leachate from wood are potentially toxic to aquatic organisms.

Treatability studies with the aim of reducing the environmental impact of wood leachate were conducted on a pilot scale as part of the scope of this thesis. The results showed, among other options, the possibility of using constructed wetlands to treat leachate. It was found that plants and aeration can affect the performance of a wetland. However, the most important factor is the time water spends in the wetland. Filter material that could be used to absorb leachate was also studied. A filter consisting of a mixture of peat and ash ash (from incinerated organic matter), was used to absorb a specific chemical group (polyphenols) in the leachate. It was also shown that polyphenols are vulnerable to ozone, representing a third viable treatment process.

Keywords: Wood leachate, Log yard runoff, Stormwater, Toxicity, Artemia salina, Vibrio fischeri, Constructed wetlands

Sammanfattning

Karakterisering av toxicitet och behandling av lakvatten från trä som genererats utomhus vid träbaserade industrier

Trä är ett naturligt råmaterial som knappast anses vara en risk för miljön. Däremot har hanteringen av trämaterial i industriell skala visat sig ha negativ inverkan på vattendrag. De flesta utredningar avseende vattenföroreningar inom träbaserade industrier har fokuserat på stora industrier med stor vattenförbrukning så som massa- och pappersbruk. Lakvatten som alstras vid kontakten mellan vatten och trä innehåller höga halter av organiska ämnen som är potentiellt farliga för vattendrag. Målet med denna avhandling är att få kunskap om ovanstående miljöproblem och möjlig behandlingar av dessa. Förorenat lakvatten skapas av industrier, där stora mängder timmer och sågspån är placerade utomhus och utsätts för regn och bevattning, såsom inom trägolv och bioenergisektorn. Man har funnit att lakning från olika träslag ger olika sammansättningar på lakvattnet, där lakvatten från ek har den högsta halten av föroreningar följt av furu. Denna undersökning visar att ek har potential att laka ut tio gånger så mycket polyfenoler jämfört med andra undersökta arter (tall, bok och lönn). Dessutom har lakvatten från ek den lägsta andelen av biologisk syreförbrukning efter 7 dagar per kemisk syreförbrukning (0,12), vilket tyder på ett potentiellt problem med den biologiska nedbrytningen av detta lakvatten. Man har även påvisat att lakvattnet från trä är potentiellt giftigt för akvatiska organismer.

Studier för att försöka minska miljöpåverkan av lakvatten från denna trädsort gjordes i pilotskala inom ramen för denna avhandling. Dessa studier visade bland annat på möjligheterna att använda sig av våtmarker som reningsmetod, där växter och luftning påverkar hur bra en våtmark fungerar. Men den viktigaste faktorn var den ökade uppehållstiden som vattnet får i våtmarken. Utöver studier av våtmarker har också ett filtermaterial studerats, filtret bestod av en blandning av torv och aska, som användes för att absorbera en specifik kemisk grupp i lakvattnet (polyfenoler). I en tredje typ av behandlingsprocess visade det sig också att polyfenoler effektivt kan brytas ned av ozon.

TABLE OF CONTENT

Preface I
List of publications III
Related publications V
Outline of the thesis and objectives VII
Abbreviations XI
Acknowledgment XIII
1. Introduction 1
  1.1.1. Chemical composition of wood leachate 2
  1.1.2. Impact of wood leachate on aquatic environments 3
  1.1.3. Treatment methods in the literature 4
    1.1.3.1. Biological treatment 5
    1.1.3.2. Physical and chemical treatments 5
2. Experiments 6
  2.1. Wood leachate characterization 6
    2.1.1. Leachate quality depending on species, age and size (Paper I) 6
    2.1.2. Toxicity depending on the wood species (Paper II) 7
  2.2. Treatability studies 7
    2.2.1. Constructed wetland (Paper III) 7
    2.2.2. Ozonation (Paper IV) 8
    2.2.3. Peat/ash filter (Paper V) 10
3. Results & discussion 12
  3.1. Leachates characterization 12
  3.2. Treatment methods 18
    3.2.1. Constructed wetland 18
    3.2.2. Peat/ash filters 21
    3.2.3. Ozonation 23
4. Conclusions 27
5. Recommendations 29
  5.1. Implications for the Society 29
  5.2 Further Research 30
6. Development of the irrigation system during the project 31
List of References 34

PREFACE

The European Union (EU) has recently announced ambitious goals on water quality. According to the European Water Framework Directive, all water bodies within the EU must achieve a good qualitative and quantitative status. This goal requires considerable work by member states.

Forestry in its various forms has always been a major industry in Sweden and has a long history of affecting Swedish water bodies. For many years, log driving (moving logs from a forest to sawmills and pulp mills downstream using the current of a river) was the most important means to transport timber from forests to industrial sites. To facilitate log driving, rivers were artificially widened and cleared of rocks and other obstacles. This physical alteration of the rivers has had devastating effects on fish populations. Later, the paper and pulp industries caused large environmental problems in Sweden. However, sometimes we learn from history, and many of these problems have been overcome.

However, less obvious problems have to be addressed to meet the EU's goals. Activities such as the storage of timber or energy biomass on impervious surfaces in open areas give rise to stormwater run-off contaminated with wood leachate. When organic material comes into contact with water, several organic molecules leach out. This process occurs during precipitation and after snow-melt, but also during wet storage after the irrigation of timber.

The potential problems of and solutions to this kind of run-off are addressed in this thesis, with the main focus being on industries handling pedunculate oak (Quercus robur).

LIST OF PUBLICATIONS

I. Svensson H., Marques M., Kaczala F., Hogland W., 2013, Leaching patterns from wood of different tree species and environmental implications related to wood storage areas. *Water and Environment*. doi: 10.1111/wej.12034

II. Svensson H., Svensson B.-M., Hogland W., Marques M., 2012, Acute toxic effects caused by leachate from five different tree species on *Artemia salina* and *Vibro fischeri*, *Journal of Biobased Materials and Bioenergy*. doi: 10.1166/jbmb.2012.1202

III. Svensson H., Ekstam B., Marques M., Hogland W., 2014, Oak leachate treated in pilot scale wetland systems - Evaluating the effects of aeration and vegetation. Submitted

IV. Svensson H., Marques M., Svensson B.-M., Mårtensson L., Bhatnagar A., Hogland W., 2013, Treatment of wood leachate with high polyphenols content by peat and carbon-containing fly ash filter. *Desalination and Water Treatment*. doi: 10.1080/19443994.2013.860883

V. Svensson H., Hansson H., Hogland W., 2014, Combined ozone and biological treatment on oak wood leachate. Submitted.

I have been involved at all stages (planning, construction, laboratory work, data analysis, and writing) of all publications together with the co-authors.

RELATED PUBLICATIONS

VI. Svensson H., Jani Y., Hogland W., Marques M., 2014, Particle size characterization of oak wood leachate: COD and toxicity distribution within different fractions. Submitted

VII. Svensson H., Hansson H., Hogland W., 2013, Determination of nutrient deficiency in stormwater from the wood industry for biological treatment. *CLEAN – Soil, Air, Water,* doi: 10.1002/clen.201300621

VIII. Svensson H., Hogland W., 2012, First year experiences from pilot scale wetland system tests, *Linnaeus EcoTech'12*, Kalmar, Linnaeus University, p. 1-8

IX. Svensson H., Hogland, W., Marques, M., 2011. Pilot scale wetland treatment of stormwater runoff from a log yard: preliminary results, *12nd ICUD International Conference on Urban Drainage*, Porto Alegre/Brazil p. 1-8

X. Svensson H., 2011. Stormwater Runoff at a Wood Manufacturing Industry: Diversity in leaching pattern from different tree species, School of Natural Sciences. Linnaeus University, Licentiate thesis p. 57

XI. Svensson H., Forest A., Geoffre M., Marques M., Hogland W., 2010, Sawdust for Treatment of Stormwater. Test on synthetic stormwater contaminated with heavy metals. *Linnaeus EcoTech'10*, Kalmar, Linnaeus University, p. 315-325

XII. Svensson, H., 2010. Leaching Test with Sawdust from Different Tree Species – Appropriateness of using them as adsorption media in wastewater and in stormwater treatment, School of Natural Sciences. Linnaeus University, Master thesis. p. 31

OUTLINE OF THE THESIS AND OBJECTIVES

This investigation is part of the research project "Integrated Approach for Industrial Wastewater and Stormwater Management in the Wood Industry Sector, Phase I (2008–2010) and Phase II (2011–2013)" carried out by the Environmental Science and Engineering Group (ESEG) at Linnaeus University, Kalmar, Sweden, and sponsored by the KK Foundation in co-operation with AB Gustaf Kähr, Kalmar Energi Värme AB, AkzoNobel (Casco Adhesives AB), Becker Acroma Sherwin-Williams Sweden Coatings KB, Anlager Svenska AB and Revatec AB. Late in 2011, the project received sponsorship from the European Regional Development Fund project "Platform for Triple Helix Collaboration on Industrial Water Conservation in Småland and the Islands". How this thesis connects to previous and ongoing work within the project can be seen in Figure 1, which shows how the work of six PhD students connects to each other within the project. That will end up with an integrated treatment system for the wastewater generated at the research site in Nybro.

The overall goal of this thesis was to produce a scientific analysis of the chemical composition of water that runs off wood storage areas, and to provide insights into how this water can be handled and treated to minimize or prevent environmental damage. This was done in co-operation with AB Gustaf Kähr in Nybro, which handles much timber from pedunculate oak at its facilities.

The research work was carried out in two steps.

1. Characterization and identification of the problem—Since the literature on the subject is scarce and existing data only describe situations for wood species other than pedunculate oak, the leachate from different wood species was characterized (Papers I and II). To be able to evaluate the information found in the literature, run-off connected to the handling and storage of wood from different species, including pedunculate oak, was studied.
2. Treatment options to minimize the environmental damage—Three strategies for the treatment of wood leachate were further investigated in this thesis (Papers III, IV and V), and their possible application to water contaminated by oak leachate was considered.

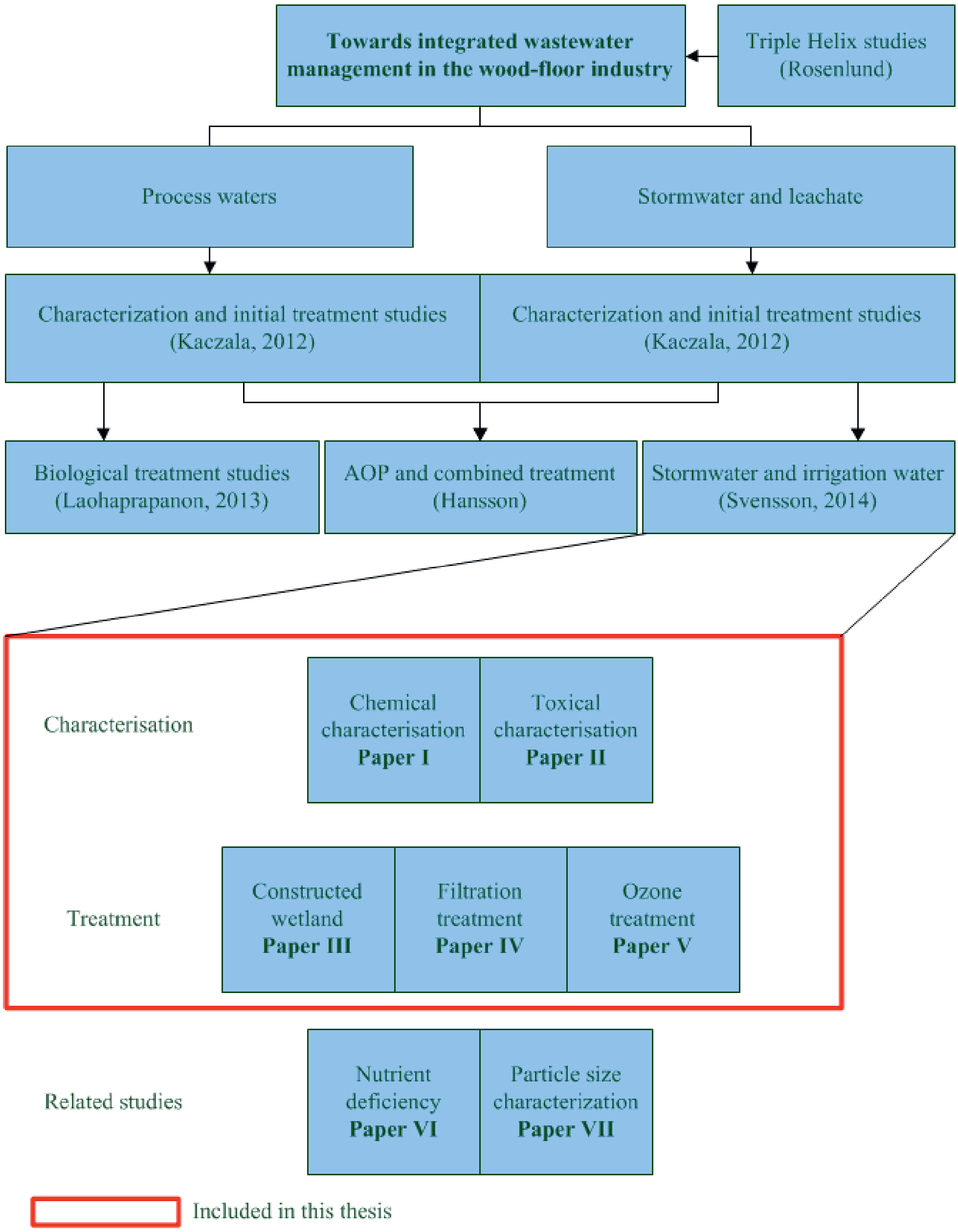

Figure 1. Diagram showing how the present thesis is related to the work carried out by ESEG group with in the project "Integrated Approach for Industrial Wastewater and Stormwater Management in the Wood Industry Sector – Phases I and II".

ABBREVIATIONS

AOS	Average Oxidation State
BOD_x	Biochemical Oxygen Demand (X= number of days)
COD	Chemical Oxygen Demand
CCA	Chromated Copper Arsenate
CW	Constructed Wetland System
DOC	Dissolved Organic Carbon
EC	Electric Conductivity
EC_{50}	50% Effect Concentration
HRT	Hydraulic Retention Time
L/S	Liquid to Solid
LOEC	Lowest Observed Effect Concentration
PP	Polly-Phenol

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This thesis was made possible not only through the author's work but also through the support of a group of people whom I wish to thank. I should start with my supervisor, William Hogland, who has provided me with the opportunity to develop this thesis. I also wish to thank my co-supervisor, Marcia Marques, who has been a valuable asset in my scientific work and a co-author of most of the publications related to this thesis.

I also wish to thank my colleague Henrik Hansson, not only for the work we performed together but also for making my working life at university easier. Without Henrik and Joacim, the coffee breaks would not have been such a pleasure. Special thanks go to members of the ESEG group: Sawanya Laohaprapanon, Fabio Kaczala, Yahya Jani, Amit Bhatnagar, Eva Kumar, Asim Ibrahim and Andre Salomão.

I wish to thank the co-authors of my scientific works outside the environmental science and engineering group, starting with Britt-Marie Svensson and Lennart Mårtensson from Kristianstad University. Both provided me with much help, and I thank them for their co-operation. Börje Ekstam from Linnaeus University also deserves many thanks for the help he provided during the studies on constructed wetlands.

Finally, I wish to thank my family at home. First, I thank my mother and father for the good work they did in preparing me for my professional life. Second, I thank Malin for understanding the time I had to spend at university—I hope we will have a good life together!

1. INTRODUCTION

It is easy to believe that storing natural products such as wood must be harmless. How could wood, which exists abundantly in forests, pose an environmental risk? However, the fact is that organic compounds are released from wood when it comes into contact with water, and these can create an environmental problem. This process is called leaching, and water contaminated with leached compounds is called leachate. When logs and residues like woodchips and sawdust are stored on impervious surfaces, there is no natural filtration and the water from rainfall, snowmelt or irrigation that contains leached contaminants from the wood. This water needs to be drained to a treatment pond or equivalent before it is discharged into the aquatic environment. If the concentration of contaminants in this leachate is too high, there could be an adverse impact on the receiving water body. The water leaching from natural wood has even been shown to be more toxic than chromated copper arsenate (CCA)-treated wood (Hingston et al., 2001) occasionally. Leaching from wood is not something unique, since any type of organic biomass can generate leachate. Leaching from barley straw, for example, has been shown to be useful in preventing algal blooms in water bodies (Gibson et al., 1990, Murray et al., 2010).

Stormwater run-off contaminated with wood leachate is found at wood-based industrial sites such as sawmills, paper mills and bioenergy plants. It is generated when water percolates through heaps of woodchips or sawdust, during irrigation for the preservation of logs, or from a layer of wood material found on top of most impervious surfaces in wood-based industrial facilities.

1.1.1. Chemical composition of wood leachate

Different problems have been identified in the literature on stormwater run-off contaminated by wood leachate. Hedmark and Scholz (2008) highlighted in their review that the main problem related to log yard run-off is the large amount of organic matter released in the stormwater. The most common proxy indicator used to express the amount of organic material in wood leachate is probably the chemical oxygen demand (COD). Depending on several variables, such as the wood species and type of material (e.g., sawdust, timber or bark), the amount of organic matter released varies. A COD concentration as high as 14,723.8 mg L^{-1} (deHoop et al., 1998) has been reported. This can be compared with the average COD of sewage in the city Kalmar, Sweden, which in 2010 was 508 mg L^{-1} before treatment and 56mg L^{-1} after treatment. Large amounts of organic matter released by wood logs and other wood materials discharged into receiving watercourses might cause anoxia.

Another indicator used in the literature to describe the amount of organic matter is the total organic carbon (TOC). COD (the most commonly used indicator) is a measure of the amount of oxygen needed to *reduce* the organic matter to CO_2 in the presence of a strong oxidizing agent, whereas TOC is a measure of the amount of CO_2 produced in the presence of a strong oxidizing agent. The most common way of measuring COD currently involves the use of toxic elements, such as chrome (Cr) and mercury (Hg). During the writing of this thesis, the possibility of stopping COD tests in Sweden has been discussed, due to the fact that mercury is banned in Sweden. COD tests should be replaced by TOC tests because of the use of Hg in COD test. During the present transitional period, some investigations and papers presented results as COD and others presented results as TOC.

Other compounds mentioned in the literature and commonly found in wood leachate are phenol, acid resins, tannins and lignin and volatile fatty acids (Hedmark and Scholz, 2008). Owing to the presence of some of these compounds, wood leachate is often reported to have a dark colour (Tao et al., 2005). Which substances found on the more detailed level compeered to proxy indicators as COD, is depending allot on wood species from which the leachate origins. However, some general differences are identified when soft wood and hardwood are considered separately.

All trees are seed-bearing plants. However, there are two distinguishable groups: gymnosperms and angiosperms. Softwoods (coniferous woods) are gymnosperms; hardwoods are angiosperms. These groups have structural differences that are not important to this thesis and therefore, not discussed. However, there are differences between the leachates generated by these groups. Generally, hardwoods (e.g., oak) have a higher content of tannins than do softwoods (Bianco and Savolainen, 1994). Softwoods often contain more lignin and terpenes than do hardwood (Fengel and Wegener, 1989).

1.1.2. Impact of wood leachate on aquatic environments

Wood leachate is often reported to be toxic to aquatic organisms. When comparing the toxicity of CCA-treated wood with that of untreated wood, the latter has been found to have a stronger effect (Baldwin et al., 1996). Different test organisms have been used to assess the toxicity of wood leachate. Some investigations have used fish such as rainbow trout (Taylor et al., 1996, Bailey et al., 1999a, Tao et al., 2005). While others have used crustaceans such as *Daphnia magna* (Taylor et al., 1996), *Crassostrea gigas* (Libralato et al., 2007) and *Artemia franciscana* (Libralato et al., 2007), or bacteria such as *Vibrio fischeri* (Zenaitis and Duff, 2002, Borga et al., 1996). Another group of organisms used to assess toxicity includes microalgae such as *Phaeodactylum tricornutum* (Libralato et al., 2011) and used *Scenedesmus subspicatus* (Kaczala et al., 2011).

Tannins and lignin are often measured as tannin & lignin (T&L) and are considered a toxic group of compounds (Bailey et al., 1999a). Both tannins and lignin have individually been demonstrated to be toxic (Libralato et al., 2011). Other substances, such as phenols, tropolones and resin acids, are likely to contribute to the observed toxic effects of wood leachate (Samis et al., 1999). In water run-off from wood storage areas, high levels of metals are often also found, especially zinc (Zn) (Bailey et al., 1999b), which could also be the main contributor to the toxic effects of leachate (Bailey et al., 1999a).

Besides its toxic effects, wood leachate can contribute to other disturbances in the receiving waters. Low pH and a dark colour are other potential problems mentioned in the literature: acidity is a well-known problem for sensitive aquatic species, and Kritzberg et al. (2014) showed that water colour could affect the food web of an aquatic ecosystem. A third problem is the risk of oxygen depletion, particularly in small streams and ponds, owing to the large amount of organic matter in wood leachate, which consumes dissolved O_2 during its oxidation. In addition, large amounts of phosphorus have been mentioned in some reports (Hedmark and Scholz, 2008).

1.1.3. Treatment methods in the literature

Many different methods have been proposed to treat the wastewater/leachate from log yards, sawmills and bioenergy storage facilities. Both physical and chemical treatment methods as well as biological treatments have been proposed. However, since the leachate composition can vary depending on the wood species and on the specific characteristic of different wood handling-facilities, a method that succeeds for one site and wood type may not work for others. It is therefore important to investigate methods that treat leachate efficiently for different wood species and storage sites.

1.1.3.1. Biological treatment

Several authors have investigated the application of biological processes to the treatment of wood leachate. Samis et al. (1999) proposed aerated lagoons, activated sludge systems and natural and artificial wetlands. Tao et al. (2006b) and Masbough et al. (2005) has shown that it is possible to treat the wood leachate in microcosmic wetlands. Woodhouse and Duff (2004) demonstrated that the use of an aerobic trickling filter is another feasible option. Other authors (Jonsson et al., 2006) showed the possibility of using a soil–plant system by irrigation of couch grass (*Elymus repens*) and willows (*Salix spp.)*.

1.1.3.2. Physical and chemical treatments

The list of proposed treatment methods is long, and it includes carbon absorption, chemical oxidation (with hydrogen peroxide, calcium hypochlorite or potassium permanganate), ozonation, chelation, coagulation, ion exchange, precipitation, reverse osmosis and sedimentation (Samis et al., 1999). However, only ozone of these methods has been investigated in more details (Zenaitis et al., 2002, Doig et al., 2006, Doig et al., 2007). Ozonation has been shown to reduce the toxicity of wood leachate (Zenaitis and Duff, 2002). Perkowski et al. (2003) also found that spiked solutions of tannins were easily degraded by ozone.

2. EXPERIMENTS

This section briefly explains the experiments related to the thesis. More detailed information can be found in the scientific papers related to the thesis.

2.1. Wood leachate characterization

The composition and concentration of contaminants in the leachate from wood are dependent on many different factors. The site of the growing trees and the age and health status of the wood at harvest might affect the content of the leachate. However, the main factor is the wood species.

2.1.1. Leachate quality depending on species, age and size (Paper I)

In Paper I, the composition of leachate from wood materials of different tree species and different wood ages and particle sizes were assessed and compared. The four wood species in this comparison were: beech (*Fagus sylvatica*), maple (*Acer platanoides*), pine (*Pinus sylvestris*) and oak (*Quercus robur*). The leachate was analysed by measurements of biological oxygen demand at 7 days (BOD_7), dissolved organic carbon (DOC, colour, phenols and T&L. Different liquid-to-solid (L/S) ratios were used in the investigation. Furthermore, the effects of the wood particles size and the storage time (aging) were investigated. Leaching was carried out in the laboratory following the Standard Method SS-EN 12457-2, with a modification to the method for assessing the S/L ratio (Paper I).

2.1.2. Toxicity depending on the wood species (Paper II)

In Paper II, the wood leachate toxicity was investigated under laboratory conditions. Two different bioindicators were used, the crustacean *Artemia salina* and the bacterium *Vibrio fischeri*. Sawdust from five wood species was assessed: beech (*Fagus sylvatica*), spruce (*Picea abies*), pine (*Pinus sylvestris*), larch (*Larix decidua*) and oak (*Quercus robur*). Leaching tests with bark obtained from oak, spruce and pine were also conducted. Toxicity assays were applied to the leachate generated from wood samples under laboratory conditions. The leachate was then used to assess acute toxicity, and the 50% effect concentrations (EC_{50}), i.e., the concentration of the wood leachate that results in 50% mortality of the test organism, was estimated for both bioindicator. The exposure time for *Vibrio fischeri* was 15 min, and that for *Artemia salina*, was 24 hours.

2.2. Treatability studies

Three different treatment options for wood leachate were examined in this thesis: a constructed wetland system (CW) on a pilot scale, ozonation and adsorption/filtration using a peat/ash filter.

2.2.1. Constructed wetland (Paper III)

A treatability study was conducted over two years for a 12-mesocosms (CW) in the wood storage area of AB Gustaf Kähr in Nybro. The wastewater to be treated was obtained from a black pond that stores stormwater running off a storage area for oak logs, woodchips and sawdust and irrigation water from the log irrigation system. The aim of this study was to examine the effects of aeration and/or vegetation on the treatment performance of the CW. The following four types of treatment experiments were conducted in triplicates (giving a total of 12 experimental units or mesocosms): control/control, vegetation/aeration, vegetation/control and control/aeration treatments (Figure 2). The vegetated tanks were planted with common reed (*Phragmites australis),* and the aerated tanks were aerated with mechanical aerators at a rate of 1680 L hour^{-1}. Construction and planting were carried out during 2011, and sampling was performed during the vegetation seasons of 2012 and 2013.

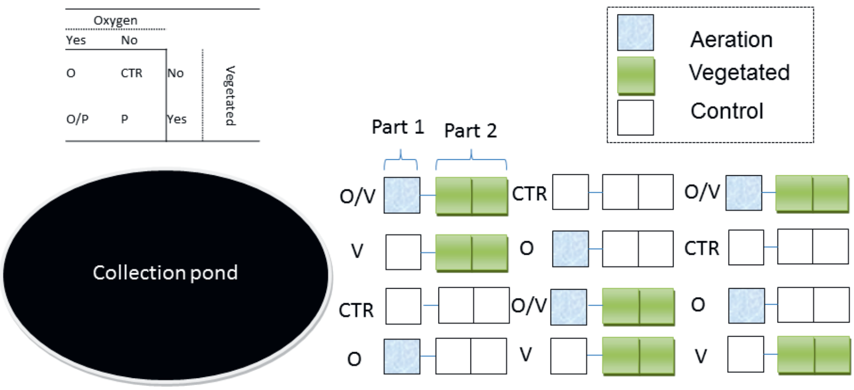

Figure 2. Experimental CW using with four different treatment combinations, each implemented in triplicate in three separate tanks, giving 12 experimental mesocosm units in total. Abbreviations: Control (CTR), Aeration (O), Vegetation (V) and Aeration + Vegetation (O/V)

2.2.2. Ozonation (Paper IV)

Ozonation is an in situ chemical oxidation treatment that is more active than a CW and requires considerably more energy. A positive aspect that supports the application of ozone to treat wood leachate that, as reported in the literature, ozone is excellent for reducing the phenol and polyphenol (PP) content. The possibility of using ozone as a treatment for wood leachate, alone or as a post-treatment step after biological treatment, was examined in Paper IV. The study was conducted using a tubular stainless-steel bubble column reactor (diameter =

8.5 cm, height = 59 cm). The treated volume in each experiment was 1.5 L. The ozone was generated from 99.5% pressurized oxygen (O2) by a water-cooled corona discharge ozone generator (ICT-10; Ozone Tech Systems, Sweden), and the ozone was passed through a stainless-steel diffuser with a pore size of 20 μm (length = 8 cm, diameter = 1.9 cm) (SD-3; Ozone Solutions, USA), as shown in Figures 3 and 4. A small bubble size is known to be an important factor in the mass transfer of ozone to water (Meza et al., 2011). The ozone concentration in the outflow from the ozone reactor was measured by an ozone monitor (Figure 3). To calculate the total consumed ozone, we calculated the difference between the total injected ozone and the outflowing ozone measured by the ozone monitor. All remaining ozone was catalytically destructed in an ozone destructor. The ozone was added at three different concentrations: 7, 50 and 100 g Nm^{-3}, the concentrations were decided (i) according to equipment limitations and (ii) to provide a sufficiently large spread of ozone input levels to enable the reliable detection and measurement of any effects. The flow rate of 1 L min^{-1} was based on equipment limitations. All experiments were conducted for 1 hour, and samples were taken after 2.5, 5, 7.5, 10, 30 and 60 min. The treated stormwater and process water were not pH corrected or buffered before treatment with ozone, because stormwater is usually generated in large volumes, and our aim was to see whether it would be feasible to use ozone without pH correction (even though adjusting the pH could enhance the ozone efficiency). pH correction would also require more technically complicated and expensive implementation in for a full-scale system.

This investigation also included a biodegradability test after the ozonation. A pulse-flow headspace respirometer and accompanying software were used. Water from a pilot-scale wetland system (Paper III) treating oak wood leachate was used as an inoculum. This water had previously been used in respirometric studies on oak wood leachate (Svensson et al., 2014). All samples were also investigated for organic molecules smaller than 1 kDa, and the ratio between the number of such molecules before and after ozonation was calculated.

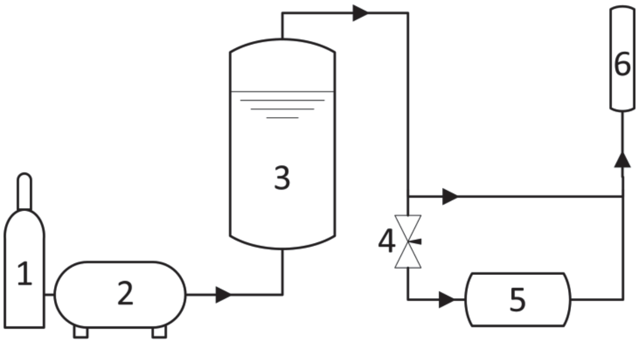

Figure 3. Ozone system used in the study. 1: O2 pressure tank. 2: Ozone generator (ICT-10). 3: Ozone reactor. 4: Needle valve. 5: Ozone monitor (BMT-964). 6: Ozone destructor (OD-0100).

Figure 4. Ozone reactor customized for the wastewater treatability tests at Linnaeus University.

2.2.3. Peat/ash filter (Paper V)

Peat and ash have been previously used by the ESEG research group for the treatment of landfill leachate (Kängsepp, 2008). Two filter materials (peat and a mixture of peat and ash) were evaluated as treatment options for wastewater contaminated with oak wood leachate. This treatability study was conducted with columns containing the absorbent filters. In total, 12 polyvinyl chloride columns with an inner diameter of 70 mm and height of 1 m were filled with filter material. Six columns were filled with peat, and the other six columns were filled with a mixture of peat and ash (Figure 5), to examine the sorption/ filtration capabilities of the two materials separately and together under dynamic conditions. Uncertainties such the breakthrough time and the risk of insufficient input stormwater were solved by packing six columns up to a level of 0.8 m and six columns up to a level of only 0.4m (Figure 5). The total volume of the columns with 0.8 m of filter material was 3 L, and that of the columns with 0.4 m of filter material was 1.5 L. The density of the peat was about 140 g L^{-1}, and that of the mixture (peat and ash) was about 280 g L^{-1}. The leachate was pumped into the columns (in downwards flow mode). Over 125 days of operation, 136 L of wood leachate was pumped through each column. The contaminants removal capacity was monitored based on measurements of COD, TOC and PP content.

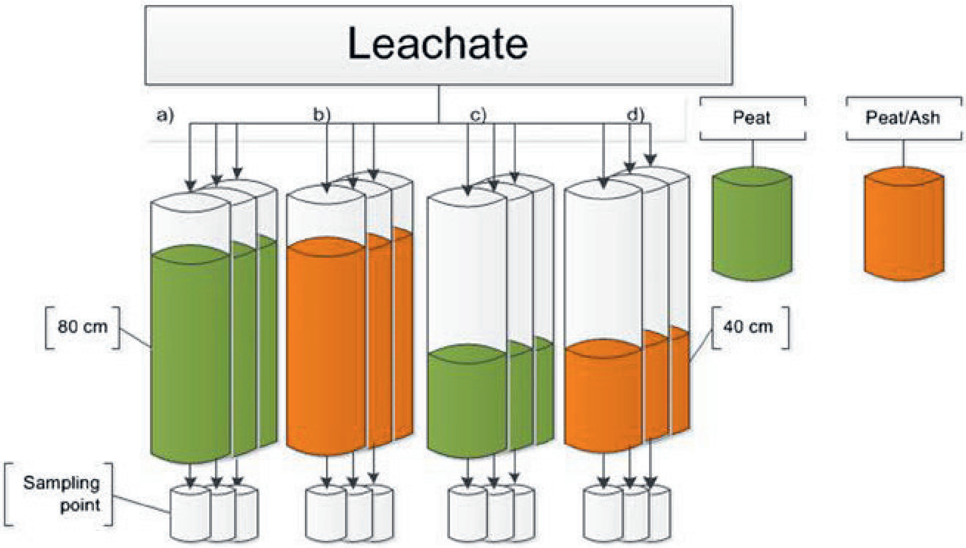

Figure 5. Four experimental set-ups: columns filled with up to 80 cm (a and b) and 40 cm (c and d) of only peat (a and c) and; peat + ash (b and d).

3. RESULTS & DISCUSSION

3.1. Leachates characterization

Two different characterization tests were conducted on the wood leachates: one physical-chemical characterization (Paper I) and acute toxicity characterization (Paper II). The physical-chemical characterization showed differences in the leachates generated by the four different wood species studied (maple, beech, pine and oak; see Table 1). The results of the acute toxicity investigation for the five wood species studied (beech, larch, spruce, pine and oak) using two different bioindicators (the crustacean *Artemia salina* and the bacterium *Vibrio fischeri*) are given in Table (2).

Water that has been in contact with wood material is characterized by a high concentration of organic matter. However, the organic substances in leachate differ among wood species. Table 1 present difference in maple, beech, pine and oak leachate in terms of pH, colour, phenols, PPs, DOC and BOD_7.

The results show that oak leaches much larger amounts of organic compounds (measured as dissolved oxygen demand) into the water phase per unit of dry matter than do the other investigated species (pine, maple and beech). During the first 24 hours of leaching, 90,000 mg of DOC per 1 kg of dry matter was released to the water phase, which is three-to-six times the DOC released per 1 kg of dry matter from the other investigated species. In addition, oak has the lowest BOD_7/DOC ratio, indicating that oak is hard to biodegrade.

Table 1: Variables measured after 24 hours of leaching at two S/L ratios (1:20 and 1:40). Values are given as averages in units of mg kg^{-1} of dry mass (± standard deviation).

Species	S/L	N	pH (s.d.)	Colour Pt-Co	EC µS m^{-1} (s.d.)	Phenols * (s.d.)	PP*[3] (s.d.)	DOC* (s.d.)	BOD_7 (s.d.)	BOD_7/DOC
Maple[1]	1:40	5	6.3 (0.4)	330 (0)	90 (20)	380 (5)	2,698 (570)	14,600 (1191)	3,462 (42)	0.24
•	1:20	5	6.8 (0.1)	440 (90)	130 (12)	290 (16)	1,100 (433)	13,200 (715)	3,106 (57)	0.23
Beech[1]	1:40	5	6.2 (0.1)	330 (0)	90 (9)	290 (14)	2,312 (283)	14,600 (587)	4,082 (127)	0.28
•	1:20	5	5.5 (0.2)	330 (0)	100 (28)	240 (17)	1,600 (582)	14,200 (619)	3,346 (14)	0.24
Pine[2]	1:40	5	4.5 (0.1)	150 (0)	70 (5)	300 (19)	3,042 (544)	33,500 (2170)	5,272 (170)	0.16
•	1:20	5	4.5 (0.1)	140 (25)	130 (7)	250 (18)	900 (67)	31,900 (3200)	5,371 (785)	0.18
Oak[1]	1:40	6	4.1 (0.1)	1,300 (58)	100 (28)	3,000 (810)	27,300 (2441)	94,000 (4887)	11,582 (1485)	0.12
•	1:20	5	4.0 (0.1)	2,130 (140)	140 (6)	2,660 (66)	33,700 (4035)	85,400 (4062)	11,441 (460)	0.14

*= mg kg^{-1} of dry mass; s.d. = standard deviation. [1)] Hardwood [2)] Soft wood [3]In Paper I PP was labelled as T&L.

The effect of repeatedly washing of wood material on the release of organic matter is discussed in Paper I. The experimental data in Figure 6 show that the DOC concentration in the leachate decreased to about 40% after the second wash, which is similar to the effect previously described (McLaughlan and Al-Mashaqbeh, 2009), where approximately 50% of the cumulative leaching of organic carbon from lingo-cellulosic material such as pine, hardwood (non-monocot angiosperms) and wood garden compost occurred during the first 24 hours. The DOC released was dramatically reduced after the second washing. Large reductions of DOC after the first washing might be attributable to the release of organic particles attached to the sawdust surface and chemical substances (cellulose, phenols and tannins and lignin, among others). However, the DOC was almost constant from the third washing onwards. After six washing cycles, the final DOC concentration in the leachate obtained in a batch test was less than 5% of the original DOC released with no previous washing.

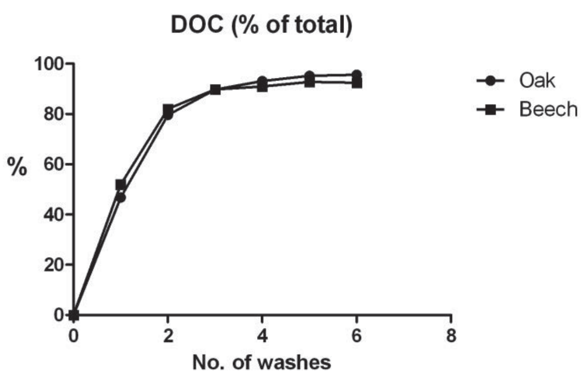

Figure 6. The accumulated leaching effect of washing sawdust repeatedly, plotted against the number of washing cycles (n = 4; standard deviations are too small to be seen).

The pH values of leachates from the studied tree species ranged from 4.1 (oak) to 6.8 (maple), as shown in Table 1. These pH differences might affect the leachate toxicity.

After normalizing the colour of the leachate (in terms of Pt-Co) towards the lowest values, which were found for pine leachate, it was found that the colour of oak leachate was 8.7 and 15.2 times the colour measured for pine. The ratios between beech and pine and between maple and pine regarding colour were 2.2 and 3.1 times respectively. The literature associates leachates of dark colour with hardwood and attributes them to hardwood timber's high tannin content (Koch, 2008, Bauch, 1984).

Phenol concentrations from 12 to 77 mg L^{-1} (240 to 3,000 mg kg^{-1} dry matter, Table 3) were recorded in the water phase after leaching tests for residues from different wood species (Paper I).

Studies of leaching behaviour in Paper I showed that the total leached DOC per unit of dry matter is affected not by the S/L ratio but by the wood species. However, at very low S/L ratios, some differences in the total amounts of pollutants leached are probably to be expected due to equilibrium between the water phase and solid phase. This interpretation is supported by the fact that, at smaller S/L ratios, larger amounts of substances leach from sawdust per unit dry matter. This hypothesis was not tested in the present study.

Acute toxicity tests indicated that different phenolic compounds in oak leachate are toxic. Oak leachate was toxic for the crustacean *A. salina*, (EC_{50} 75%) and even more toxic for *V. fischeri* (Microtox ®) (EC_{50} 26%) (Table 2). However, pine had a similar toxic effect, despite its low concentration of phenolic compounds compared with oak. The three other tree species investigated (spruce, larch and beech) had significantly lower toxic effects. However, the leachate from spruce bark exhibited toxic effects similar to those of oak and pine leachate.

Table 2: Acute toxicity for A. salina in a 24 hour test (n = 3) and for V. fischeri (Microtox©) in a 15-min test (n = 1). Results are presented as the percentage dilution of the leachate with wastewater that yielded the lowest observed effect concentration (LOEC) for A. salina, and the percentage dilution that yielded the EC50 for A. salina and V. fischeri. Coefficients of variation are given in the parentheses for A. salina.

Species	***LOEC A. salina***	***EC_{50} A. salina***	***EC_{50} V. fischeri***
	Sawdust		
Oak	68%	75% (8.23)	26% (1.30)
Pine	45%	79% (7.91)	2% (6.38)
Spruce	79%	-	<100%
Beech	86%	-	98% (2.61)
Larch	79%	-	62% (2.08)
	Bark		
Oak	79%	90% (7.97)	18% (1.39)
Spruce	80%	89% (5.89)	5%(1.11)
Pine	83%	85% (0.00)	1% (1.17)
	Field samples		
Irrigation water oak	91%	-	-
Irrigation water spruce	91%	-	-
Stormwater oak	79%	81% (2.16)	42% (1.41)

Furthermore, analysis of the samples (Table 2), revealed that irrigation water had low toxicity compared with the stormwater and leachate from sawdust, which apparently tends to be more toxic than the wastewater produced from bark. When comparing the acute toxic responses exhibited by the two different bioindicators, it was found that the bacteria used in Microtox® are more sensitive than the crustacean A. salina to all tested leachates. The most toxic leachate is that released from pine bark, in which only 1% of the wastewater is sufficient to inhibit 50% of the bacterial population.

3.2. Treatment methods

Three different treatment methods were investigated within the scope of this thesis. The possibility of using a CW was investigated, with a focus on aeration and vegetation. Furthermore, a filter consisting of peat and ash was investigated. Finally, as a chemical method the possibility of using ozone was investigated.

3.2.1. Constructed wetland

During 2011, 12 experimental units of CW mesocosms were installed. Six of them were planted with the emergent wetland plant P. australis, which took one year to become established. The CW's operation and treatment performance were then monitored over a 2-year period (2012–2013).

The results from this investigation are presented and discussed in Paper III. The main finding was that the treatment efficiency was dependent on the hydraulic retention time (HRT), while vegetation and aeration made only small contributions to the treatment performance (Table 3). The CW with a 28-day HRT removed about 47% of the COD. COD removal increased to 49% with the addition of vegetation, and to 52% with vegetation plus aeration. The removal efficiency for PPs was slightly higher, within the range 53%–64% depending on the treatment (Table 3). The results show that CWs are a feasible option for the treatment of wood leachate, depending on the volume that needs to be treated, since the area required increases with the total leachate volume if the HRT is fixed. However, since emergent plants (vegetation) have so little impact, it is possible to plan deeper ponds that can store more leachate/wastewater per square meter.

The low contribution of vegetation and aeration found in present study are somewhat surprising. Aeration has been shown to have positive effects on the treatment of wood leachate (Tao et al., 2007, Taylor et al., 1996, Zenaitis and Duff, 2002, Woodhouse and Duff, 2004). However, only two publications have compared aerobic and anaerobic treatments (Tao et al., 2007, Taylor and Carmichael, 2003). The presence of emergent plants has also been reported to be an important factor for enhancing the treatment performance of a CW. Planted CWs have often been reported to be more efficient than unplanted ones for domestic wastewater treatment (Karathanasis et al., 2003). Planted CWs have been used for the treatment of wastewater contaminated with wood leachate (Masbough et al., 2005, Tao et al., 2006a, Tao et al., 2006b). Plants are thought to enhance wastewater treatment by creating spaces in which epiphytic microbes can thrive. However, some studies concluded that plants made little difference to the overall treatment performance (Tao et al., 2006b). Similar results were obtained in the present investigation, in which vegetation yielded only a marginal improvement in the treatment performance. This result is explicable by the very slight effect of epiphytic bacteria on wood leachate found in another study (Tao and Hall, 2004). This past study of CWs used in the treatment of wood leachate found that free-floating bacteria were responsible for about 26% of the total pollutant degradation rate and that bacteria in sediments were responsible for about 73%, whereas bacteria living as epiphytes on plants accounted for only 1%. This is in line with the results obtained in the present study. The results from the present investigation support the recommendation of Tao and Hall (2004) to construct deep, unplanted ponds instead of shallow ponds with emergent plants.

Table 3: Treatment in Part 1 (first part of the treatment) and in Parts 1+2 (the whole treatment) of the mesocosms. Average reduction rates (g m–3 day–1) during the year. Significant differences from the control treatment are shown by the P-value in a linear mixed model. The reduction (%) is the average total reduction.

	Part 1 (HRT = 14 days)		**Part 1+2 (Total HRT = 28 days)**			
	O	**CTR**	**O**	**V**	**O/V**	**CTR**
COD reduction (g m^{-3} day^{-1})	10.0	9.5	11.0	10.6	11.0	9,5
P value	0.249	-	0.002	0.018	0.002	-
COD reduction (%)	30	27	52	49	53	47
PP reduction (g m^{-3} day^{-1})	1.6	0.9	1.4	1.2	1.3	1.1
P value	<0.001	-	<0.001	NS	<0.001	-
PP reduction (%)	36	21	64	58	64	53
Colour reduction (g m^{-3} day^{-1})	14.4	29.2	99.6	99.6	109.0	84.7
P value	<0.001	-	NS	NS	0.002	-
Colour reduction (%)	9	18	50	50	51	41

O = aerated tank; V = vegetated tank (*P. australis*); CTR = control; NS = not significantly different from the control ($P > 0.05$).

3.2.2. Peat/ash filters

The sorption/filtration of contaminants in water using different absorbents is a widely used technique, and the most common material used is probably activated carbon. In Paper IV, the feasibility of using a sorbent/filter composed of peat or a mixture of peat and ash was evaluated. The mixture of peat and ash yielded better TOC removal efficiency than did a filter consisting of only peat. It should be noted that the removal efficiency of the mixture was approximately three times that obtained with peat only (Figure 7). However, the removal efficiency for PPs did not differ between the two filter types, even though the peat and ash mixture provided faster absorption than did peat alone (Figure 8). In total, 1 kg of peat+ash removed 18–23 g TOC, while 1 kg of peat alone removed 11–18 g TOC. The difference between the filters was smaller for PPs: both filters removed around 10 g TOC per 1 kg of filter material.

The difference in TOC sorption described in Paper IV can be explained by the differences in the filter types' cation content and pH. Ash contains a large amount of cations, especially calcium (Ca). Cations are known to interact with different humic substances, and this process enhances sorption via the Fuoss effect (Randtke and Jepsen, 1982). Furthermore, the peat and ash used in this study were known to contain large amounts of Ca (8,410 mg kg^{-1}), in addition to other cations. Cations are known to interact with natural organic compounds in two ways: by establishing site-specific strong binding, and by establishing weak binding through the presence of counter ions in the vicinity of the organic molecule or through electrostatic attraction (Averett et al., 1989). Weak bonds are present in all molecules and depend on their carboxylic acid content and the structural arrangement of the chemical groups in the molecule, whereas strong bonds are very organic-specific and are not always present. The literature has reported that the characteristics of interactions with Ca vary broadly with a change in the source of humic substances (Kango et al., 1986). Another study (Liao and Randtke, 1986) has suggested that the complexation of natural organics with Ca might lead to more stable complexes or aggregations. In another study, Chandrakanth et al. (1996) suggested that Ca preferentially interacts with oxygen-containing functional groups. The interactions with Ca vary depending on the organic content. The interaction of natural organics with cations results in the creation of various molecular species, but the available data are limited because of the unknown equilibrium constants and the different interactions between cations and various organics, which involve several mechanisms.

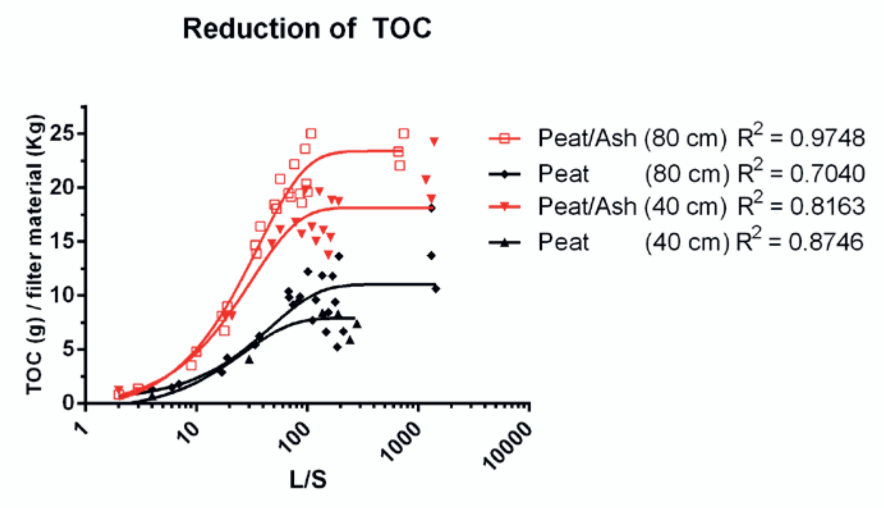

Figure 7. Accumulated reduction of TOC (in g per kg filter material) versus the L/S ratio. The height of the column filter is given in parentheses.

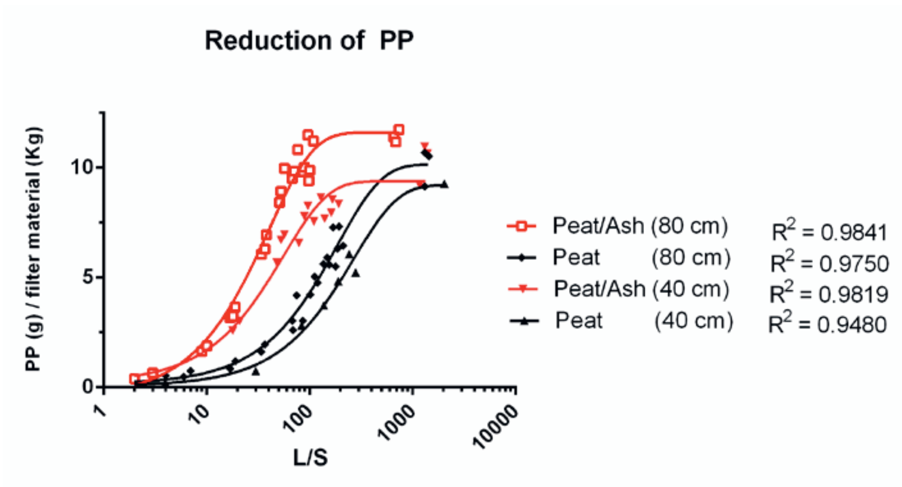

Figure 8. Accumulated PP reduction (in g per 1 kg filter material) versus the L/S ratio. The height of the column filter is given in parentheses.

3.2.3. Ozonation

Ozonation can be considered as a pre-treatment step (followed by, for instance, biological treatment) or as a stand-alone treatment. In Paper V, the application of ozone was evaluated as a treatment method for PP-rich oak leachate. As expected, the PP reduction was higher than the COD and TOC reductions (Table 4). With an applied dose of 4 g O3 L^{-1}, around 90% PP reduction was achieved, regardless of the initial PP content, while the amount of COD removed varied from 31% to 73% depending on the initial concentration.

PPs are often reported as being the most problematic substances in wood leachate because of their toxicity and strong effect on water colour. As seen in Table 4, ozone is effective in oxidizing PP compounds. As discussed in the Introduction, ozone reacts more quickly with certain types of aromatic and aliphatic compounds, such as phenols. This was very clearly shown in this study, with the reduction reaching 80%–90% (Figure 9). This confirms previous results reported in the literature (Zenaitis and Duff, 2002) showing that phenol toxicity is reduced by ozonation.

We found positive effects from combining the pre-treatment of wood leachate with ozone and subsequent biological treatment. This differs from the results reported by Zenaitis and Duff (2002), who found no improvement from using ozone as a pre-treatment. This could be because of the difference in the wood species studied.

The largest effect on biodegradability was found when 70% of the total amount of PPs was removed. However, after removing 35% of PPs, this positive effect on PP degradation did not occur; in fact, a significant toxic effect was seen. This could be because of the generation of toxic by-products of oxidation (Gottschalk et al., 2009). This indicates that for ozone to be an effective treatment, it needs to be applied in a relatively large dose. When oxidizing mixed-pollutant water with ozone or other methods, oxidation by-products can be produced, and these by-products can be equally as toxic as, or more toxic than, the original compound (Renou et al., 2008, Naddeo et al., 2011) . Furthermore, the sample with the highest fraction of organic molecules smaller than 1 kDa after ozonation was shown to be the most biodegradable. This fraction is expected to be the most biodegradable fraction, since in most cases, only monomers and oligomers of molecular sizes smaller than 1 kDa are able to cross bacterial membranes (Cadoret et al., 2002). The drop in pH for the other samples can be explained by the formation of organic acids as by-products of the oxidation (Ntampou et al., 2006) and shows that, for this oxidation to be applied as a pre-treatment prior to the use of a biological system, some additional buffering system would be required.

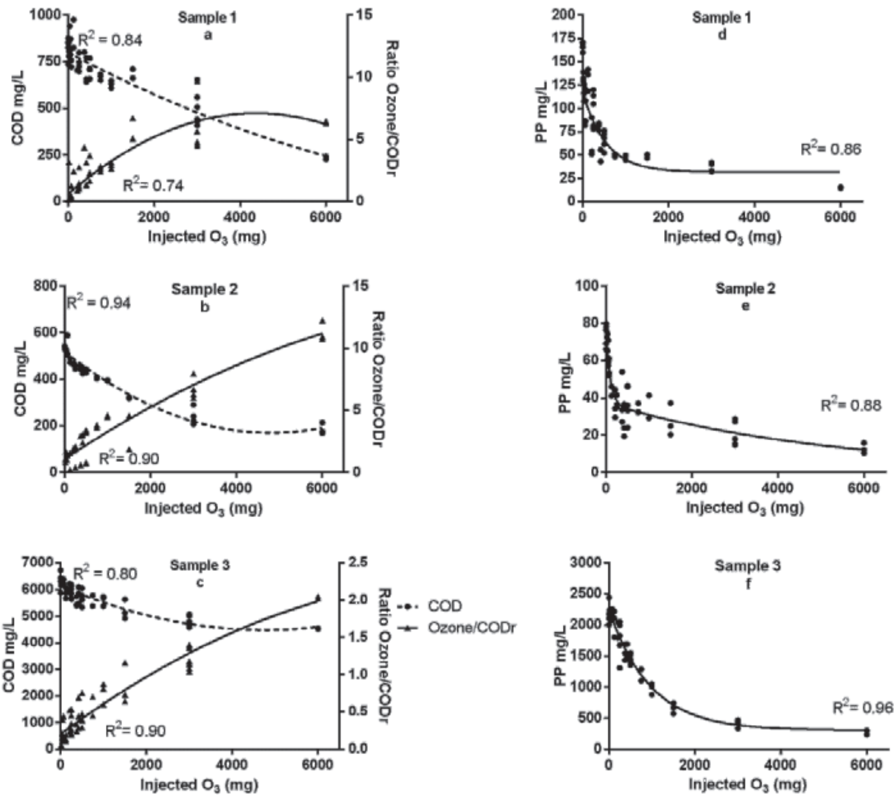

Figure 9. Graphs a–c show the results of ozonation per milligram of ozone injected for the COD and the ratio of ozone injected to COD removed (CODr). Graphs d–f show the PP reduction fitted to a two-phase decay equation.

Table 4. Total reduction after injecting 4 g L–1 ozone into the reactor. Range in parentheses (n = 3).

Parameter	Sample 1	Sample 2	Sample 3
O_3 in (g L^{-1}) / initial COD (g L^{-1})	5.0 (0.2)	7.0 (0.2)	0.7 (0.0)
COD reduction (mg L^{-1})	620 (10)	350 (50)	1960 (720)
% reduction	73 (2)	66 (8)	31 (12)
O_3 in (g L^{-1}) / initial TOC (g L^{-1})	11 (0.8)	17 (0.8)	1.5 (0.0)
TOC reduction (mg L^{-1})	220 (3)	120 (30)	630 (190)
% reduction	62 (1)	50 (11)	24 (7)
O_3 in (g L^{-1}) / initial PP (g L^{-1})	24 (1.3)	55 (9.5)	1.9 (0.1)
PP reduction (mg L^{-1})	150 (1)	60 (10)	1920 (60)
% reduction	91 (1)	83 (7)	87 (3)
O_3 in (g L^{-1}) / initial colour (g L^{-1})	1.0 (0.0)	1.4 (0.1)	0.2 (0.0)
Colour reduction (mg L^{-1})	4600 (30)	2800 (60)	19000 (120)
% reduction	97 (1)	97 (2)	91 (1)
AOS pre-treatment	0.38 (0.30)	0.49 (0.22)	0.48 (0.36)
AOS post-treatment	1.43 (0.1)	1.55 (0.14)	0.84 (0.25)
pH pre-treatment	6.2 (0.1)	6.3 (1.3)	3.8 (0.3)
pH post-treatment	3.4 (0.0)	3.3 (0.2)	2.5 (0.1)

4. CONCLUSIONS

From Paper I, is it possible to conclude that the wood species generating the leachate is the main factor affecting the leachate's chemical composition. Different wood species have different compositions of organic molecules. This is not a surprise. However, it suggests the importance of considering the wood species being handled when choosing leachate treatment methods. A factory handling pedunculate oak wood can be expected to generate a type of leachate that will require more careful handling of the stormwater run-off from the log yard compared with one handling beech wood.

Paper II shows that the acute toxicity of wood leachate depends on the wood species. Acute toxicity has been measured using the EC50 value, which suggests the concentration that would be harmful to the aquatic ecosystem receiving the contaminated run-off. In this study, acute toxicity was measured with the bioindicator Vibrio fischeri after 15 min of exposure and with Artemia salina after 24 hours. It is likely that a longer exposure time would affect the surviving organisms even at concentrations lower than the EC50 reported. Since toxicity is always a matter of concentration, the toxic effect on receiving watercourses caused by the wood leachate depends on the size and volume of the watercourse and the contaminant concentration in the wood leachate.

Papers III, IV and V presented examples of different treatment methods that could be used to reduce the impact caused by wood leachate on the receiving watercourse. Passive biological treatment systems (so called because they have some self-management capability after construction), such as CWs, have been used to treat similar contaminated water. However, filtration systems, such as the one investigated in Paper V, also have a certain self-management capability, except that the filter must be replaced once it is saturated with contaminants. Ozone treatment, on the other hand, requires more active operation, e.g., running and maintaining equipment such as pumps and ozone generators. In addition, this technology consumes energy during treatment. All methods tested have been proved to work. However, their relative suitability depends on different site- and wood species-specific factors. The construction of a CW requires a large treatment site area because of the HRT required during treatment; filter beds, on the other hand, require much less space. Ozone requires a relatively high energy input but is also the fastest method studied here.

5. RECOMMENDATIONS

5.1. Implications for the Society

As mentioned in the Introduction, the EU's environmental goals regarding the quality of water bodies are ambitious. The storage and handling of wood has the potential to affect strongly the surrounding aquatic environment. This thesis has pointed out that the environmental impact of wood leachate varies depending on the wood species handled; therefore, it is important to consider the type of industry and the tree species being processed when assessing possible environmental impacts, and then to decide on the optimal technologies to apply for environmental protection.
Most problems with run-off contaminated with wood leachate relate to the large amount of organic matter therein and its toxicity. However, leachate colour, pH and toxicity have also been identified as potential problems.

The effects on the environment are also, however, highly dependent on the characteristics of the receiving watercourse. Toxicity is always a matter of concentration/dilution, although the total load can also be an important variable under some circumstances. Toxicity in this thesis was mainly found to be associated with naturally occurring organic molecules released in the water by wood. These compounds are degradable, and after complete degradation, they are converted to carbon dioxide. This is in contrast to many other toxicants, such as heavy metals and polychlorinated biphenyls. The same principle of using concentration to explain toxicity works for organic matter (i.e., COD or TOC). The risk of leachates high in COD and TOC causing anoxia in receiving watercourses depends on the latter's size/volume and baseline O_2 level.

However, even if the run-off is not sufficiently concentrated to have a visible impact on the receiving watercourse, such as increased fish mortality, wood leachate still has the potential to alter the aquatic ecology via chronic effects. Changes in the penetrability of the water by light (solar radiation) or the available organic matter can affect the food web. The amount of nitrogen and phosphorus reaching the watercourse can also have important effects. Therefore, taking a precautionary approach, wood leachate should be always treated before reaching natural watercourses. The appropriate extent of the treatment, on the other hand, could depend on the sensitivity and/or fragility of the receiving watercourse and its ecosystem, and on the wood species producing the leachate.

5.2 Further Research

Further investigations are needed to develop treatment methods that are as cost effective as possible. One potential system that requires more investigation is infiltration systems. Furthermore, the extant literature only covers some of the industrial wood species found in the northern hemisphere. Wood species not investigated in the present thesis, should be characterized in terms of their leachate compositions and toxicities to aquatic organisms. Furthermore, wood is handled all over the world. What is the environmental impact of wood handling in New Zealand or Brazil? Are any wood species even more problematic for the natural environment than oak?

6. DEVELOPMENT OF THE IRRIGATION SYSTEM DURING THE PROJECT

This thesis has been a co-production with the participation of AB Gustaf Kähr and Linnaeus University. It started in 2009 when AB Gustaf Kähr commenced planning for a new timber irrigation system at Nybro, Sweden. The development of the irrigation system during the project has therefore been closely connected to the university's activities. After a short period of investigations the construction of the irrigation system began, even though the researcher saw that the impact of oak leachate was not fully comprehended from the industry side. In the initial planning stage for the irrigation system, the university-based research team presented a proposal about how the system could be constructed. This plan included an irrigation system with recirculation and stormwater harvesting. At that time, the university team considered this the best approach from an environmental perspective. The concept was based on the fact that there are no large rivers around the industrial sites in Nybro, Sweden, and therefore, the only alternative water source is groundwater. Using this was considered a waste of valuable water resource from the university team's view-point. A second goal of stormwater harvesting was to reduce stormwater run-off and thereby minimize the spread of contaminants in leachate. The recirculation of irrigation water would close the system, and run-off would only escape to the natural environment during extreme events.

For the recirculation project to work, the university team considered continuous purification of the contaminated water within the system to be necessary. Otherwise, contaminants would build up within the recirculation system, which could ultimately be hazardous to the working environment. To this end, the university team proposed a system including both aerated ponds and vegetative filters.

For various reasons, the plant was not constructed entirely according to the university team's recommendations. However, the site does currently have an irrigation system that uses rainwater and recycles irrigation water. The treatment system with aerated ponds and vegetative filters proposed by the university team has not been constructed. However, the scientific data presented in this thesis show that the most important treatment factor is the retention time, and the company's construction of big ponds is actually appropriate in this regard. These big ponds serve as both storage tanks and treatment ponds. However, recirculation means that organic matter continuously builds up in the system, and this build-up of recalcitrant organic matter was expected to cause the treatment to stop working eventually. Therefore, a vegetative filter was also constructed (Figure 10). The plan is to use this filter for constant draining of the system. It is expected that this will continuously lower the amount of organics in the system.

Figure 10. Photograph of the existing vegetative filter immediately after construction in 2013 (and therefore without vegetation).

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