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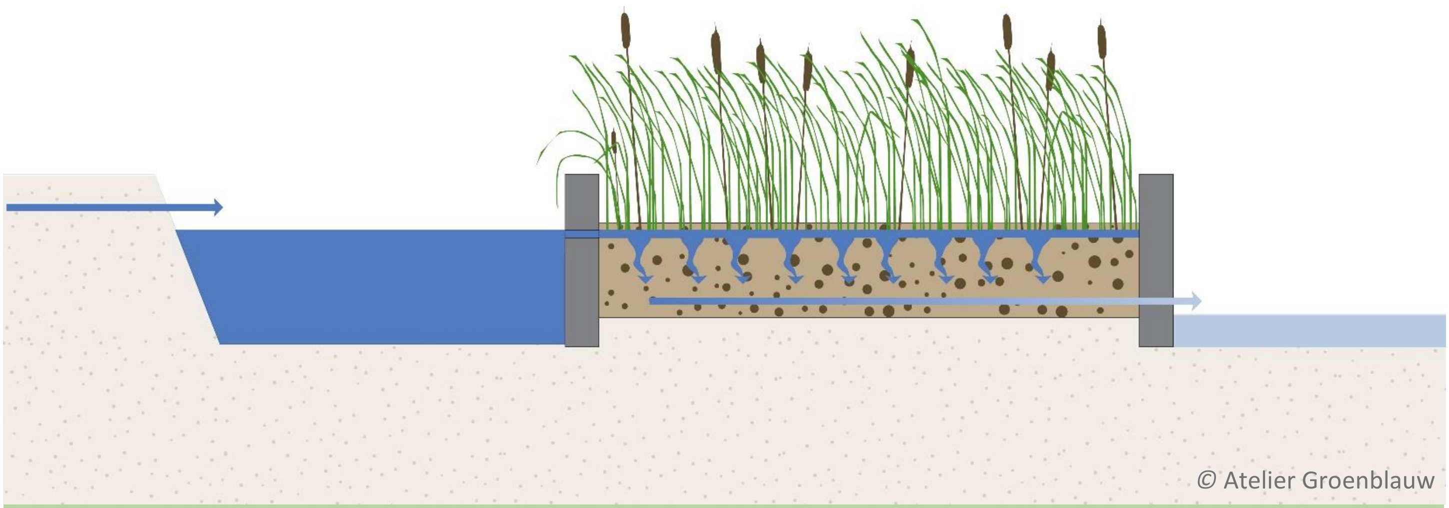
A study into the current state of helophyte filtration systems and potential improvements by using edible plants



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2021, Renkum

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A study into the current state of helophyte filtration systems and potential improvements by using edible plants

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Preface

To conclude my study of Applied Biology at the Aeres University of Applied Sciences, I here present my bachelor thesis. This literary research will provide a description of helophyte filters and investigates the possibility of improving their edibility. I was very passionate about this subject and am quite proud of the end product. But in truth, I could not have achieved it without the help and care of my family, friends and mentor. First of all, I would like to thank Ton Hilhorst that gave me the idea of this thesis during my internship at Artis. And secondly, I say thank you to my mentor Erwin Roze, for his advice and patience. And a great thank you to my friend and roommate Luuk Jungerling, who has been my rock during this process. And to my parents that have always been there for me, thank you for everything.

Abstract

As population density increases, the pollution of water is accelerated. Helophyte filters have shown great potential for the treatment of wastewater, and by adding the role of food cultivation by using edible aquatic macrophytes, the value of these systems can increase. The goal of this bachelor thesis is to give an overview of the current helophyte filters available, and to see if they could, potentially, be improved into a food source. This is researched using the following research question: "**What are the prospects of using a helophyte filter as a food source?**". To answer this question, three sub-questions will be explored; 1. How does a helophyte filter work? 2. What types of helophyte filters are there? 3. Which edible plant species can be used in a helophyte filter, and what should be considered regarding the use of these species? Helophyte filters can purify a range of wastewater based on a combination of biological, chemical and physical processes that are induced by the interaction of plants, micro-organisms, the soil and pollutants. There are different types of helophyte filters, and when designing a helophyte filter, it is important to tailor the system to the type of wastewater that needs to be treated. Currently, the number of application areas for helophyte filter technology has significantly expanded. A wide variety of plants is used in helophyte filters all over the world, consisting of not only helophytes but also other aquatic macrophytes. Many of these plants already have edible parts, and apart from being used as a human food source, they can also serve for other uses. In order to improve the long-term performance of constructed wetlands, plant harvesting regimes should be conducted. And by timing these strategically, the amount of greenhouse gas emission will be minimizes, while also maximising the amount of nutrients harvested. However, it is important to do sufficient research before deciding to harvest and eat species from a helophyte filter system. As this report shows helophyte filters have the potential to be more than just a method of sustainable water filtration. Both future and current filters, globally in use, hold nutrient-rich and exciting food sources ready for the picking.

Nederlandse samenvatting

Naarmate de bevolkingsdichtheid toeneemt, versnelt de vervuiling van water. Helofytenfilters hebben aangetoond een groot potentieel te hebben voor de behandeling van afvalwater, en door de rol van voedselteelt toe te voegen door gebruik te maken van eetbare aquatische macrofieten, kan de waarde van deze systemen verhogen. Het doel van deze bachelor scriptie is om een overzicht te geven van de huidige helofytenfilters die beschikbaar zijn, en om te kijken of deze mogelijk kunnen worden verrijkt tot een voedselbron. Dit is onderzocht aan de hand van de volgende onderzoeksvraag: "**Wat zijn de vooruitzichten van het gebruik van een helofytenfilter als voedselbron**?". Om deze vraag te beantwoorden worden drie deelvragen onderzocht; 1. Hoe werkt een helofytenfilter? 2. Welke soorten helofytenfilters zijn er? 3. Welke eetbare plantensoorten kunnen in een helofytenfilter worden gebruikt, en wat moet er overwogen worden met betrekking tot het gebruik van deze soorten? Helofytenfilters kunnen een scala aan afvalwater zuiveren op basis van een combinatie van biologische, chemische en fysische processen die worden geïnduceerd door de interactie van planten, micro-organismen, de bodem en verontreinigende stoffen. Er zijn verschillende soorten helofytenfilters, en bij het ontwerpen van een helofytenfilter is het belangrijk om deze geschikt te maken voor het type afvalwater dat moet worden behandeld. Inmiddels is het aantal toepassingsgebieden van de helofytenfiltertechnologie aanzienlijk uitgebreid. Een grote verscheidenheid aan planten wordt gebruikt in helofytenfilters over de hele wereld, die niet alleen uit helofyten bestaan maar ook uit andere aquatische macrofieten. Veel van deze planten hebben al eetbare delen en kunnen naast het gebruik als voedselbron voor de mens, ook voor andere doeleinden dienen. Om de prestaties van helofytenfilters op de lange termijn te verbeteren, moeten er oogstregimes voor de planten worden uitgevoerd. En door deze strategisch te timen, zal de uitstoot van broeikasgassen worden geminimaliseerd, terwijl ook de hoeveelheid geoogste voedingsstoffen wordt gemaximaliseerd. Het is echter belangrijk om voldoende onderzoek te doen voordat men besluit om soorten uit een helofytenfiltersysteem te oogsten en te eten. Zoals dit rapport laat zien hebben helofytenfilters de potentie om meer te zijn dan alleen een methode van duurzame waterfiltratie. Zowel de toekomstige als de huidige filters, die wereldwijd worden gebruikt, bevatten waardevolle en veelbelovende voedingsbronnen, klaar om geplukt te worden.

1 Introduction

Water is an essential part of our planet and covers about 71 percent of the Earth's surface. However, only 2.5% of that water is 'fresh' and of this, a mere 1% can be found in liquid form (IAEA, 2011). Fresh water is used in vast amounts to sustain the human population (Biswas & Tortajada, 2019). As population density increases, so accelerates the contamination of water (Valluri, n.d.). In addition, the degradation of water quality also contributes significantly to water scarcity (Jia, Klemeš, Alwi, & Varbanov, 2020). Fortunately, water is not an expendable natural resource as, for example, oil, gas or coal are. When properly managed, it can be reused indefinitely (Biswas & Tortajada, 2019). It is, however, important that water is used efficiently, so that water wastage is limited and that as little water as possible is contaminated. The water that is contaminated should be cleaned (Groot-Zevert, 2009; Mateo-Sagasta, Zadeh, & Turral, 2017).

When human activity has been the cause of the contamination of water, it is generally called wastewater. This includes domestic sewage as well as industrial sewage and storm sewage. Domestic sewage (single house or households), or municipal wastewater (clusters of houses or community), contains water used in residences and businesses (Crites, Middlebrooks, Bastian, & Reed, 2014). Industrial sewage is water that has been used during the production process of a commercial product. Storm sewage is rainwater that has picked up debris, grit, nutrients and chemicals through urban and agricultural areas (Nathanson & Ambulkar, 2019). In addition to being a contributing part of storm sewage, agricultural ecosystems also play a major role in water pollution (Mateo-Sagasta et al., 2017). Agriculture uses approximately 80% of water resources worldwide (Velasco-Muñoz, et al., 2018). And these farms discharge large quantities of contaminants, such as organic matter, but also agrochemicals or drug residues, into bodies of water (Mateo-Sagasta et al., 2017).

Today, a wide variety of technologies is available to clean wastewater chemically, physically and/or biologically (Crini & Lichtgouse, 2019). Wastewater treatment, as it is called, removes the impurities from wastewater before it reaches aquifers or natural bodies of water (Nathanson & Ambulkar, 2019). Water treatment plays a major role in the control of water pollution. In addition to these conventional systems, there are also natural possibilities (Tunçsiper, 2019; Nathanson & Ambulkar, 2019). Using these natural possibilities will mitigate and reduce the burden to the environment (Han, et al., 2019). An example of a natural option is the use of bacteria and fungi to biologically clean water in so-called biofilters. Other organisms widely used for water filtration are plants. A technology utilising the symbiosis of both plants and micro-organisms is the helophyte filter (Nanninga, 2011).

Helophyte filters are generally known as water tight basins designed to intercept and remove a range of pollutants from contaminated water, by passing wastewater through reed beds, usually consisting of common reed (*Phragmites australis)* (Jing, Lin, Shik, & Lu, 2008; Nanninga, 2011). The name helophyte filter is most commonly used in the Netherlands, synonyms used for these filters are: constructed wetlands, constructed reed beds, artificial wetlands and planted soil filters (Nanninga, 2011).

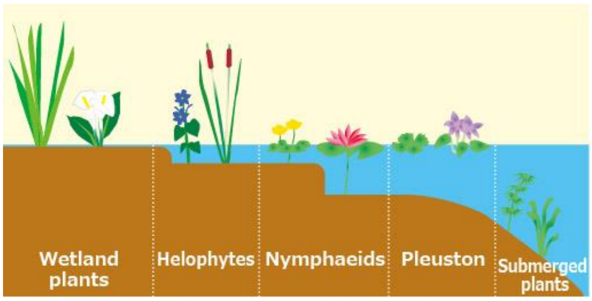


Figure 1: Aquatic plants. Spatial distribution of different plant types occurring in natural wetlands. (Adventest, 2016)

Wetlands are an example of a naturally occurring helophyte filter. The helophytes that these wetlands contain, are also known as emergent macrophytes. They are plants whose living environment is in between that of aquatic plants and terrestrial plants (Figure 1). The roots of a helophyte are buried in wet, often submerged, soil, and their buds overwinter under water (Coops

& Geilen, 1996). However, the rest of the plant; consisting of the stems, leaves and flowers, extends above the water surface (Duistermaat, 2020). The plants growing in these riparian areas, in between land and water, affect the water system by removing pollutants, sediment and nutrients from inflowing surface and groundwater, thereby cleaning the water (Sender & Grabowski, 2016). Natural wetlands served as an example for the first man made wetlands, or helophyte filters, built in the 1950's and 1960's, as a way to exploit the natural water purifying processes, copied from nature (Moinier, 2013; Nanninga, 2011). However, it was decades later, in the 1980's, that the use of artificially built helophyte filters for water filtration rapidly grew, due to an increase of knowledge on this technology (Dunbabin & Bowmer, 1992). Currently, helophyte filters are used all over the world, and the amount of applications has rapidly increased (Nanninga, 2011). And despite the fact that these filters are generally known as helophyte filters in the Netherlands, more types of macrophytes can be used, such as submerged, free floating, and floating-leaved plants (Environmental Pollution, 2008).

As the trend in landscape management increases, the technology of helophyte filters expands. Its full potential however, has not been reached (Zehnsdorf, Blumberg, & Müller, 2018). Constructed wetlands have even become popular in landscape architecture; attractive filters serve as green 'wetland' roofs in the form of helophyte mats. According to a recent study by Zehnsdorf *et al.* (2019), helophyte mats reduce hydraulic loads on the sewers by increasing the evapotranspiration of rainwater. This is due to the reduced stomata regulation of helophytes, which makes their evapotranspiration level higher than that of terrestrial plants. Moreover, the root zone of the mat delays and reduces the flow of rainwater, as it serves as a retention space (Zehnsdorf, et al., 2019). Helophyte filtration is now used as a relatively cheap method to filter water globally. Low construction and operating costs, durability, and its sustainable ecological function are major selling points, especially for developing countries that lack economic means and expertise to manage more conventional water filtration systems (Guo, et al., 2019). However, the filters have a large space requirement, which varies from tens of square meters up to several thousands of square meters (Vulto & Beltman, 2007). A next improvement of this system could be made, following principles of the circular economy, by adding the role of food cultivation to the list of benefits using edible aquatic macrophytes, thereby increasing the value of helophyte filtration systems.

The goal of this bachelor thesis is to give an overview of the current helophyte filters available, and to see if they could, potentially, be improved into an edible food source. This is researched using the following research question: "**What are the prospects of using a helophyte filter as a food source?**". To answer this question, three sub-questions will be explored; 1. How does a helophyte filter work? 2. What types of helophyte filters are there? 3. Which edible plant species can be used in a helophyte filter, and what should be considered regarding the use of these species?

The 1st question will clarify the biology of aquatic macrophytes and how these biological principles make a helophyte filter work. The 2nd question will explain which types of helophyte filters are available, how helophyte filters are built and their current applications. And the 3rd question is designed to explore which plant species are currently used, which species are edible, and what needs to be considered when using helophyte filters as a food source.

2 Method

To answer the research question; "**What are the prospects of using a helophyte filter as a food source?"**, a literature review was conducted. This chapter will clarify how the information has been collected by describing the used databases as well as the applied search terms. Furthermore, this chapter will describe which criteria a source had to meet in order to be included in this literature study.

In chapter 2.1, the used search engines with their web-link are presented. In order to find relevant sources, specific keywords were selected for these databases. The general keywords and applied combinations of these keywords with other words, are presented in paragraph 2.2. To ensure source relevance, found sources were subsequently screened with the criteria described in paragraph 2.3. Thereafter, all the relevant sources that passed the criteria were listed in a source matrix, described in paragraph 2.4.

2.1 Used databases

In order to find a wide variety of both scientific and non-scientific sources about helophyte filters, multiple online search engines and books were used. These online scientific searches were done with the use of Google scholar, Science direct, Wiley, Springer Link, GREEN-I and the online library provided by the Wageningen University. Non-scientific sources were gathered by using the search engine Google. These online search engines and their weblink are presented in Table 1, together with the books that were used and their ISBN-number.

Table 1: Consulted databases and their weblink

Consulted database	Weblink
Google Scholar	https://scholar.google.com
Google	https://www.google.com
GREEN-I	https://www.greeni.nl
Science direct	https://www.sciencedirect.com
Springer Link	https://link-springer-com
WUR Library search	https://www.wur.nl/en/Library.htm
Wiley	https://onlinelibrary-wiley-com
Consulted books	**ISBN-number**
Heukels' FLORA van Nederland	9789001589561
Essential biology (11^{th} edition)	978-0134093413

2.2 Search terms

This paragraph will display the general keywords and combination words that were used in the search engines listed above (see Table 2). All searches were carried out with the aim of answering the research questions. The use of combination words ensured the accuracy of the search, and were only added to general keywords if it would lead to more relevant results. Both English and Dutch keywords were used.

Table 2: Used keywords and their combinations

General keywords	Combination words
English	
Helophyte	Species OR edible OR plants OR function OR role OR adaptation OR oxygen availability
Helophyte filter/Constructed wetlands/Artificial wetlands/Planted soil filters/reed beds/ constructed reed beds	edible OR “edible plants” OR species OR systems OR uses OR appliances OR applications OR functions OR creating OR mechanism OR “making a” OR types OR process OR costs OR examples OR improvements OR innovations OR usage OR biodiversity OR biodiversity increase OR harvest OR harvesting regime OR wastewater treatment OR food production OR biomass harvesting OR benefits
Wastewater	removal OR treatment OR recycling
Water treatment	helophytes OR biological OR filter
Grey water	Reuse OR recycling OR wetland OR treatment system OR organic filter
Inundated plants	Oxygen transport OR biology OR aerenchyma
Natural alternatives	For water treatment OR for water filtration OR for water purification
Common reed/*Phragmites australis/P. australis*	Uses OR edible OR roofing material OR history Or consumption OR harvest
Duckweed/ *Lemna minor/ L. minor*	Uses OR edible OR consumption OR harvest
Common bulrush/ *Typha latifolia/ T. latifolia*	Uses OR edible OR consumption OR harvest
Dutch	
Helofyt	*soorten OR eetbaar OR planten OR werking OR rol*
Helofytenfilter/moerasfilter/rietfilter/rietbedfilter	*Eetbaar OR “eetbare planten” OR soorten OR plantensoorten OR systemen OR werking OR toepassingen OR functies Or maken OR bouwen OR mechanisme OR process OR kosten OR voorbeelden OR verbeteringen OR innovaties OR ontwerp OR biodiversiteit OR biodiversiteits verhoging OR oogst OR afvalwater OR voedselproductie OR voedselproductie*
Afvalwater	*Zuiveren OR recyclen OR schoonmaken OR helofytenfilter*
Water zuivering	*helofyten” OR biologisch OR filter*
Riet	*Dak OR gebruiken OR ontwikkelingen*

2.3 Criteria source selection

To guarantee that the literary study only made use of relevant sources, all sources were passed through the criteria of Table 3. Sources that met these requirements were included in the source matrix of paragraph 2.4. For this review the year of publication was not part of the criteria, as it might be useful to draw a picture on how helophyte filters have changed through the years.

Table 3: Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Sources were written in Dutch or English	The sources were written in a language other than Dutch or English
Peer reviewed scientific reports OR credible non-scientific sources, such as unpublished scientific work or government reports	The sources are not peer reviewed scientific reports and also not credible non-scientific sources
Sources that contribute in answering one or more research questions	The sources do not contribute in answering one or more research questions

2.4 Source matrix

A source matrix was made to summarize and keep a clear overview of all the sources that passed the selection criteria (Table 4). This matrix includes the title, subject, and date of publication and will ensure that sources will be easy to find again.

Table 4: Source matrix example

Title	Subject	Date of publication	APA	Scientific article? Yes/No

3 Results

3.1 How does a helophyte filter work?

This chapter will clarify the biology of aquatic macrophytes, and how these biological principles make a helophyte filter function. Furthermore, the common pollutants found in the wastewater will be named together with the physical, chemical and biological processes that take place in the helophyte filter that remove these pollutants.

3.1.1 The biology of aquatic macrophytes

Like all plants, aquatic macrophytes are sessile organisms that are permanently confined to their site of germination (Žádníková, Smet, Zhu, Van Der Straeten, & Benková, 2015). They are greatly dependent on their surrounding environment to provide the necessary building blocks, such as energy from sunlight and nutrients (e.g. nitrogen and phosphate), to grow and develop (Coops & Geilen, 1996). To make up for their lack of mobility, plants have developed unique mechanisms along their evolution that provide them with adaptive plasticity, thus allowing them to adjust to their environment (Žádníková, et al., 2015).

One of the most essential factors in the survival of plants is water (Yang, et al., 2011). However, when a plant is partly or fully submerged, it lives in reduced conditions that can negatively affect plant growth and survival (Coops & Geilen, 1996). Photosynthesis, for example, is hampered when light has to travel through often murky water in order to reach the inundated plant parts (Jackson, 2008). Furthermore, in aquatic systems the oxygen concentrations are much lower compared to the atmosphere (Caraco, Cole, Findlay, & Wigand, 2006). This limits the oxygen transport through the plant and makes it hard for the roots to receive enough oxygen for respiration (Colmer, 2003; Brix, 1994b).

To overcome the limitations of these compromised environments, aquatic macrophytes have developed certain adaptations in their way of growth (Weissner, et al., 2006). For instance, helophytes grow long stems in order to have a large part of the plant situated above water, allowing them to capture more light for photosynthesis (Coops & Geilen, 1996). Moreover, they are often able to elongate their stem and leaves with increased vigour when water level rises, which helps restore contact with the aerial environment (Jackson, 2008). To counter the anaerobic conditions around the plant roots, aquatic macrophytes have developed the ability to supply their roots with oxygen produced from photosynthesis in the above-water plant parts (Polprasert & Kittipongvises, 2011). The oxygen travels from the leaves to the roots through specific areas of tissue called 'aerenchyma' (Colmer, 2003). Aerenchyma, as shown in Figure 2, is modified parenchyma tissue composed of large intercellular air cavities, that allows for an effective gas exchange between the plant organs above water and submerged tissues (Gao, et al., 2020).

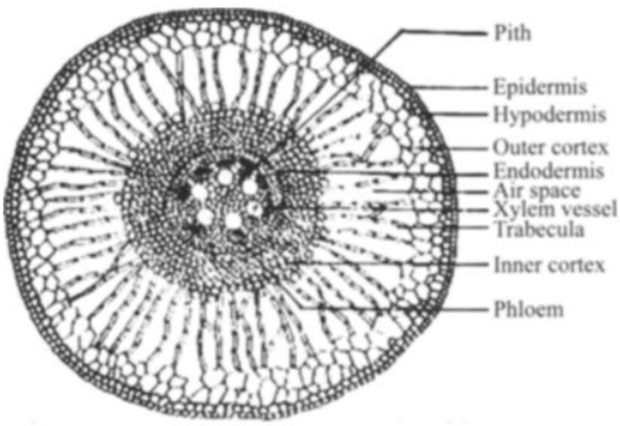


Figure 2: Cross section of the root of a water hyacinth (Qaisar, et al., 2005)

In addition to ensuring a sufficient amount of oxygen in the plant roots, there is also oxygen released into parts of the root system and the rhizosphere, illustrated in Figure 3 (Stottmeister, et al., 2003). The rhizosphere can be described as the zone of soil around plant roots that is influenced by the presence and activity of the root (Richardson, Barea, McNeill, & Prigent-Combaret, 2009). It is a dynamic and multifaceted environment, where physical, chemical and biological processes take place that are induced by the interaction of plants, micro-organisms, the soil and pollutants (Stottmeister, et al., 2003; Richardson, et al., 2009; Pérez-Jaramillo, 2019). The rhizosphere helps plants to access essential nutrients through the aerobic decomposition of organic matter, and alleviates against those that are toxic through the formation of an oxidised layer around the roots (Coops & Geilen, 1996; Richardson, et al., 2009). Furthermore, the plant roots interact with a diverse population of micro-organisms such as nitrifying bacteria. The oxygen released from the roots is subsequently utilized by these bacteria to decompose organic matter. This symbiotic relationship between the helophytes and the micro-organisms living in their root zones, plays a key role in the removal of contaminants from wastewater (Nanninga, 2011; Abissy & Mandi, 1999).

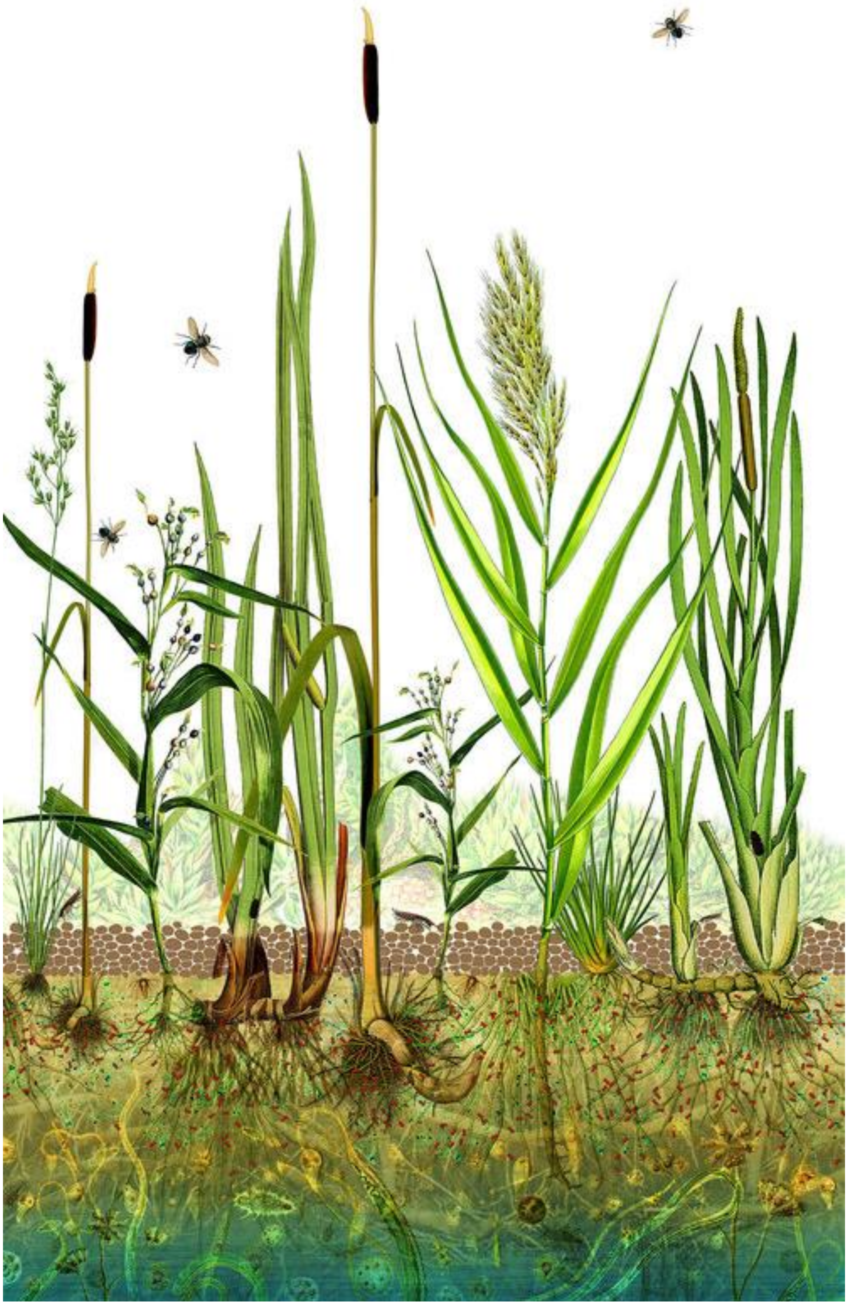


Figure 3: The aquatic macrophytes shown with their roots and surrounding micro-organisms (exaggerated) (OOZE, 2017)

3.1.2 How do helophyte filters function?

Over the last decades, the use of helophyte filters for the treatment of wastewater has increased (Wu, Zhang, Ngo, Guo, & Liang, 2017). These constructed wetlands have been reported as the clean and effective alternative to conventional wastewater treatment technology, with low-energy cost, low maintenance and operational costs and high pollutant removal capacity (Wu, et al., 2017). As in natural wetlands, the wastewater is treated with a technique that uses the natural purifying functions of micro-organisms, soil and vegetation (Haberl, et al., 2003; Zhang & Hong, 2006).

There are different types of helophyte filters, which will be further discussed in chapter 3.2. However, the wastewater treatment principles are similar for all systems (Haberl, et al., 2003). During the passage, various complex physical, chemical and biological processes take place that are induced by the interaction of plants, micro-organisms, the soil and pollutants (Stottmeister, et al., 2003). These removal mechanisms are largely determined by the types and number of micro-organisms, and the oxygen supply available to these microbes, as well as the chemical conditions and hydraulic conductivity of the substrate (Haberl, et al., 2003).

Common pollutants

Constructed wetlands are a natural alternative in treating wastewater that have found to be effective in the removal of various contaminants. They can remove commonly encountered pollutants such as benzene, ethylbenzene, toluene, xylenes, heavy metals and suspended solids (Raneiri, Gorgoglione, Montanaro, Iacovelli, & Gikas, 2014). Suspended solids in wastewater are mostly food residue, clothes particles, hairs, skin cells and colloidal material (Nanninga, 2011). In domestic wastewater, faecal matter is part of the suspended solids as well. However, the largest solids are usually already filtered out before entering the helophyte filter. The ratio of organic/inorganic solids in domestic wastewater is generally about 1:1, but this can differ per place and type of wastewater (Nanninga, 2011).

Furthermore, helophyte filters can also remove pathogens, pharmaceutical contaminants, phosphorus (P), inorganic nitrogen (N) and organic compounds such as petroleum hydrocarbons, organic carbon and organic pollutants. In wastewater, phosphorus is present in multiple forms, but mainly as the inorganic and stable orthophosphate, the unstable compound with multiple P atoms: polyphosphate, and as a phosphate bound to organic particles: organic phosphate (Nanninga, 2011). Its origin is mostly washing detergent, dishwashing soap and food particles (Metcalf & Eddy, Inc., 2004). It is a highly reactive substance that is always bound to another element; most commonly to oxygen, which forms phosphate (PO_4^{3-}) (Urry, L. A., Cain, M. L. 1., Wasserman, S. A., Minorsky, P. V., Reece, J. B., & Campbell, N. A. (2017). Nitrogen enters the influent mostly via urine, or as a compound of household chemicals; usually in the form of ammonium (NH_4^+) with low concentrations of nitrite (NO_2^-) and nitrate (NO_3^-), as a result of some biological processes (Vymazal & Kröpfelová, 2008). Depending on the pH of the water and soil, nitrogen can also occur in the form of NH_3 instead of NH_4^+. However, in the case of most helophyte filters (with a pH of 7) this is not the case (Nanninga, 2011). Moreover, the removal of nitrogen and organic compounds from wastewater is enormously important. This is because an uncontrolled discharge of nitrogen into natural water fosters its eutrophication, and untreated organic materials often deplete the dissolved oxygen concentration in open water, which will lead to the death of aquatic organisms (Saeed & Sun, 2012).

Physical processes

The physical processes that take place in a helophyte filter are filtration, sedimentation and physical adsorption. Filtration and sedimentation are the main processes that remove suspended particulate matter and are predominantly responsible for the removal of organic material (Environmental Pollution, 2008; Abissy & Mandi, 1999). Filtration occurs when particles and micro-organisms are sieved out by the rhizomes or the used medium. The type of medium used determines the permeability of the filter, for example; sand will filter out much smaller particles than gravel. Furthermore, the roots and stem movement by the wind can be accredited to the prevention of clogging in the medium, which will maintain the hydraulic conductivity. Hydraulic conductivity is the measure of ease with which a liquid can flow through a membrane of porous medium (Shackelford, 2013; Nanninga, 2011). In Figure 4, the medium is shown as the beige coloured section, in which the blue arrows show the path of filtration. Sedimentation is the process in which particles sink to the bottom of the water. Adsorption is the adhesion of atoms, ions or molecules to a surface. This will create clumps of loose particles that will be easier to filter out. Especially phosphorus and heavy metals can be removed through physical adsorption. For the adsorption of phosphorous, iron particles and zeolite are often used, and can be added to the medium (Nanninga, 2011; Environmental Pollution, 2008). Additionally, the amount of time that the wastewater stays in the helophyte filter is a factor that greatly influences the treatment efficiency. Also the rate in which the wastewater is added to the filtration system can impact the level of treatment accomplished (Nanninga, 2011).

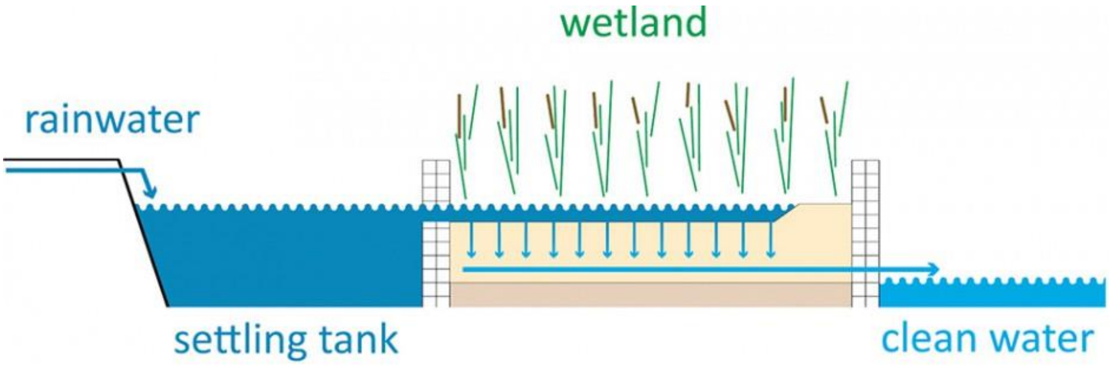


Figure 4: An example of a helophyte filter with beige coloured medium and reeds drawn as helophytes. © Atelier Groenblauw *(Atelier Groenblauw)*

Chemical processes

Chemical processes that take place include adsorption to organic matter, exposure to excreted biocides, oxidation and UV radiation. Chemical adsorption is the main process in the removal of phosphate, one of the most important contaminants. The process is dependent on the presence of substances that contain Ca, Fe, and Al (such as clay and calcite particles), which can be present in the matrix of a filter bed (van Buuren, Hartjes, & Kilian, 1998). However, the used media often do not contain great quantities of these particles, and therefore the removal of phosphate in this way is generally low. Biocides are excretions that macrophytes can produce and release into the rhizosphere, which can kill pathogenic bacteria (Alufasi, et al., 2017). Furthermore, oxidation happens through the created aerobic conditions around the roots of the plants. Oxidation is the process where chemical bonds are broken down by the highly reactive nature of oxygen molecules, for example in the formation of rust in which iron is oxidated. Part of these broken down pollutants can be taken up by the macrophytes present in the filter, which then serve as nutrients for growth and development. Lastly, UV radiation is effective in the removal of pathogens, mostly in free water flow constructed wetlands. The radiation inactivates micro-organisms in the wastewater by damaging the DNA or the organisms. This however, depends on the amount of vegetation used in the filter, as vegetation impedes sunlight penetration (Alufasi, et al., 2017).

Biological processes

The biological mechanisms in helophyte filters correspond to those in common wastewater treatment processes. Biological processes are processes regulated by organisms, and in helophyte filters these are mainly heterotrophic bacteria. These heterotrophic bacteria are attached to the plants underground organs (the roots and rhizomes) and the media surface. By using aerobic and anaerobic oxidation they can break down organic material, thus filtering the water. As mentioned in chapter 3.1.1, the oxygen required for aerobic degradation is supplied through the stems of the helophytes. And in this aerobic zone, two important mechanisms take place: ammonification and nitrification (van Buuren, Hartjes, & Kilian, 1998).

Ammonification happens when soil bacteria decompose organic matter from plant or animal decay, and will release ammonium ions (NH_4^+) into the soil (Figure 5). Ammonium is also produced during nitrogen fixation, which is the conversion of inert nitrogen gas (N_2), first of all into ammonia (NH_3), and then into ammonium, by bacteria found in the soil and roots (Colmer, 2003). During nitrification, ammonium is converted to nitrites (NO_2^-) and then to nitrates (NO_3^-), as shown in Figure 5, which can be taken up directly by plants. This conversion is done by nitrifying bacteria and uses oxygen. The bacteria in the soil can also convert nitrates back into atmospheric gas (N_2), which is called denitrification, also illustrated in Figure 5 (Nanninga, 2011). Furthermore, the aerobic zone is unfavourable for enteric bacteria as they are either obligate or facultative anaerobes (Shingare, Thawale, Raghunathan, Mishra, & Kumar, 2019). Enteric bacteria include pathogens that could be dangerous for humans, such as Shigella spp., Salmonella spp. and Escherichia coli (Shingare et al., 2019).

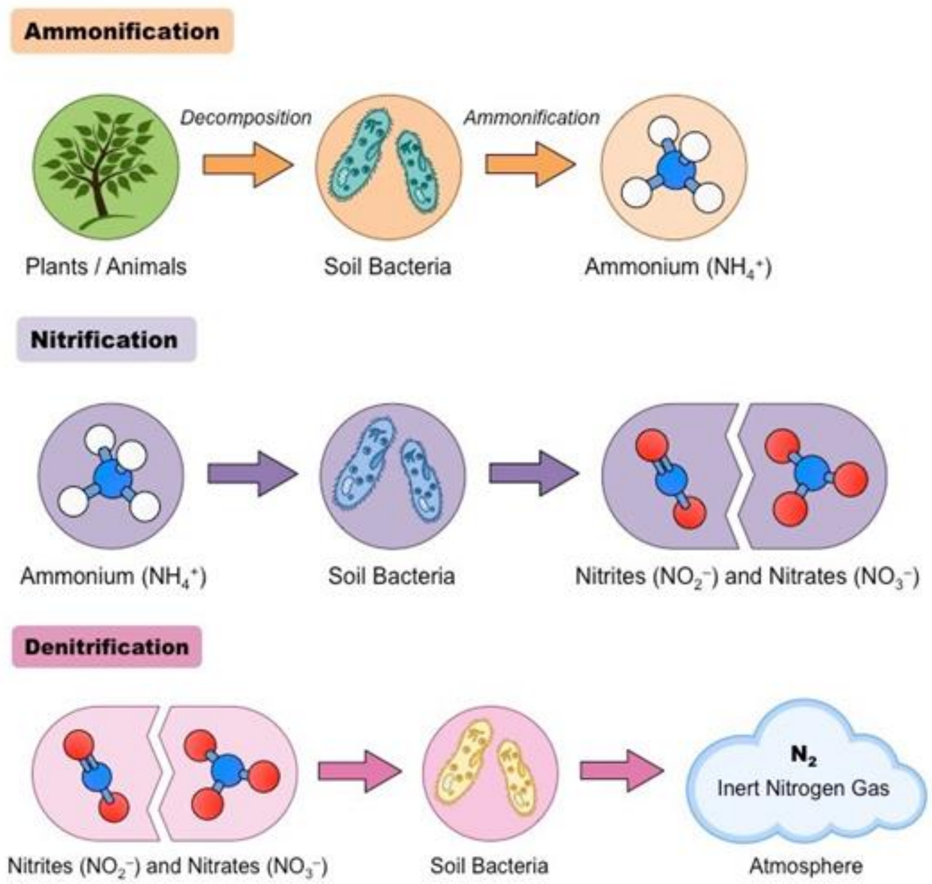


Figure 5: Ammonification, Nitrification and Denitrification processes (Cornell, 2016)

3.2 What types of helophyte filters are there?

This chapter will explain which types of helophyte filters are available, how they are built with the considerations that need to be taken beforehand, and some of their current applications.

3.2.1 What types are there?

Helophyte filters can be categorized according to the type of macrophyte growth, as well as the wastewater flow path. They are often classified into two types: free water surface (FWS) and sub-surface flow (SSF), but there are also hybrid systems possible. The general rule of thumb is that the final effluent quality improves with the complexity of the facility (Environmental Pollution, 2008). Figure 6 shows an overview of the different types of helophyte filters.

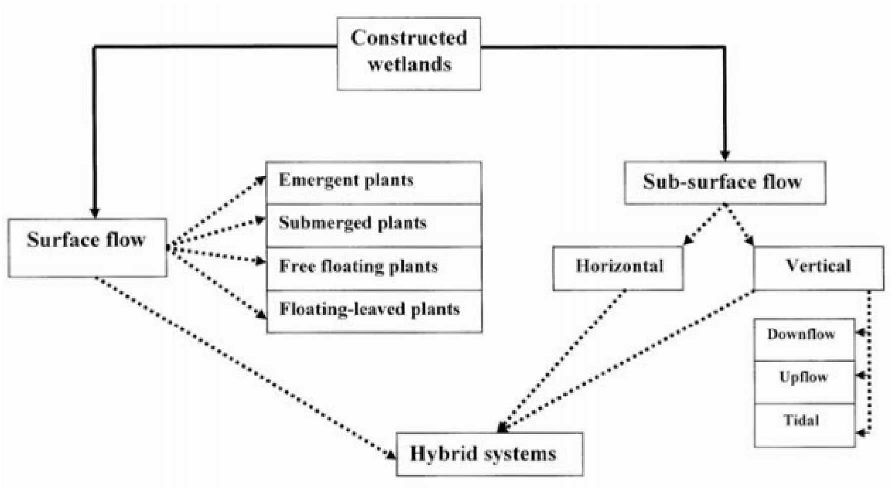


Figure 6: Classification of constructed wetlands (Environmental Pollution, 2008)

Free water surface flow path (FWS)

In the FWS systems, presented as surface flow in the image above, the water flows horizontally over the bottom basins or channels, filled with soil or another medium that can support the rooted vegetation. An example of a FWS system is shown in Figure 7. The water flows through the unit at a relatively shallow water depth (usually 20-40 cm above the helophyte bed) and with a low flow velocity (Maucieri, Barbera, Vymazal, & Borin, 2017). More than 50% of the surface is generally covered by vegetation, which allows for a great deal of contact between the wastewater and reactive biological surfaces. This dense vegetation makes FWS systems efficient in the removal of organics through microbial degradation and in the removal of solids through settling and filtration (Maucieri, et al., 2017). These systems also allow for good nitrification and denitrification processes and can achieve sustainable levels of phosphorus (P) removal. However, they are very land-intensive compared to SSF systems (Nanninga, 2011). Depending on the macrophytes used, FWS constructed wetlands can be classified in four groups: emergent plants, submerged plants, free floating plants and floating-leaved plants, as illustrated in Figure 6 (Environmental Pollution, 2008; Polprasert & Kittipongvises, 2011). Most systems use a single species or the combination of an emergent species with a submerged species (Gorgoglione & Torretta, 2018).

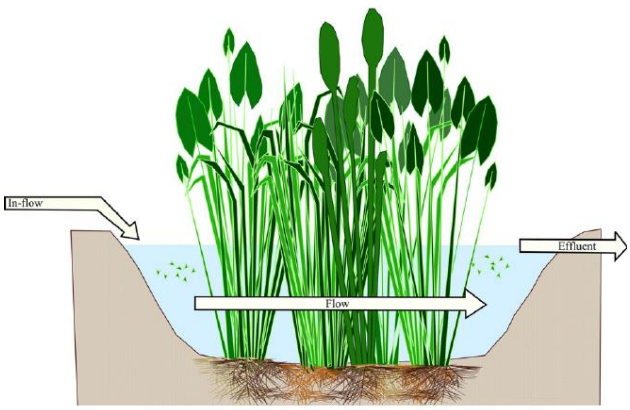


Figure 7: Free water surface flow helophyte filter (White S. , 2013)

Sub-surface flow path (SSF)

Constructed wetlands with a SSF system have the wastewater flowing under the surface of the soil, through porous media, such as aggregates or gravel with which the basin is filled (Srivastava, Yadav, Garaniya, & Abbassi, 2019). These filters generally have a much higher hydraulic conductivity compared to the FWS system and therefore a more efficient removal of pollutants (Nanninga, 2011). Moreover, sub-surface flow systems can be further subdivided into horizontal sub-surface flow (HSSF) and vertical sub-surface flow (VSSF), as shown in Figure 6.

Horizontal sub-surface flow path (HSSF)

In horizontal flow, the wastewater is continuously added, on one side of the helophyte filter, from which it slowly flows through the medium in a more or less horizontal fashion, until it reaches the other side where it is collected (Gorgoglione & Torretta, 2018). During this path the wastewater will come into contact with a network of aerobic, anoxic and anaerobic zones. In Europe, HSSF helophyte filters are commonly called “Reed beds”, coming from the fact that Common reed (*Phragmites australis)* is most often used in these systems. Moreover, HSSF systems have good BOD and suspended solids-removal, but very poor nitrification rates. The following Figure 8 shows an example of a horizontal helophyte filter (Gorgoglione & Torretta, 2018).

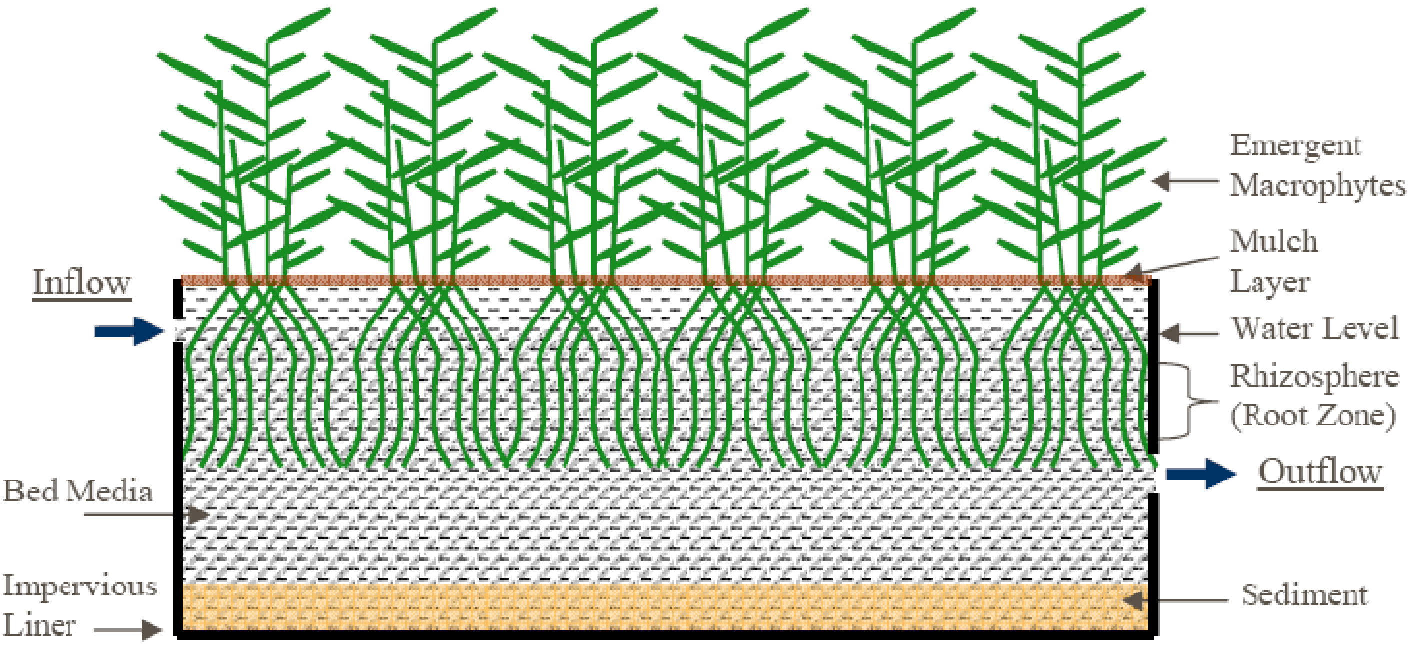


Figure 8: Horizontal sub-surface flow helophyte filter (Weber, 2016)

Vertical sub-surface flow path (VSSF)

SSF filters with a vertical flow, as shown in Figure 9, have the wastewater distributed on top of the basin, and collected at the bottom by drainage pipes. That is to say, they comprise of a flat bed of graded gravel topped with sand in which macrophytes are planted. The top layer of gravel differs in size fraction of the bottom layer. Moreover, vertical flow systems are intermittently filled with a large batch of wastewater, thus flooding the surface and letting it drain afterwards. This wastewater then gradually percolates down through the medium until it reaches the bottom where it can be collected. By intermittent dosing after filtration, the bed can refill with air. This ensures good oxygen filtration throughout the medium, that allow for nitrification and BOD removal, but poor removal of suspended solids (Environmental Pollution, 2008; Nanninga, 2011).

VSSF systems could be further categorized into down-flow and up-flow, based on whether the wastewater is fed onto the surface or to the bottom of the system (Environmental Pollution, 2008). SSF helophyte filters can be seen as more efficient than FWS because they require less land area than a FWS helophyte filter, as there is more surface contact between the water and the medium, bacteria and plant roots, which results in a more efficient pollutant removal (Nanninga, 2011).

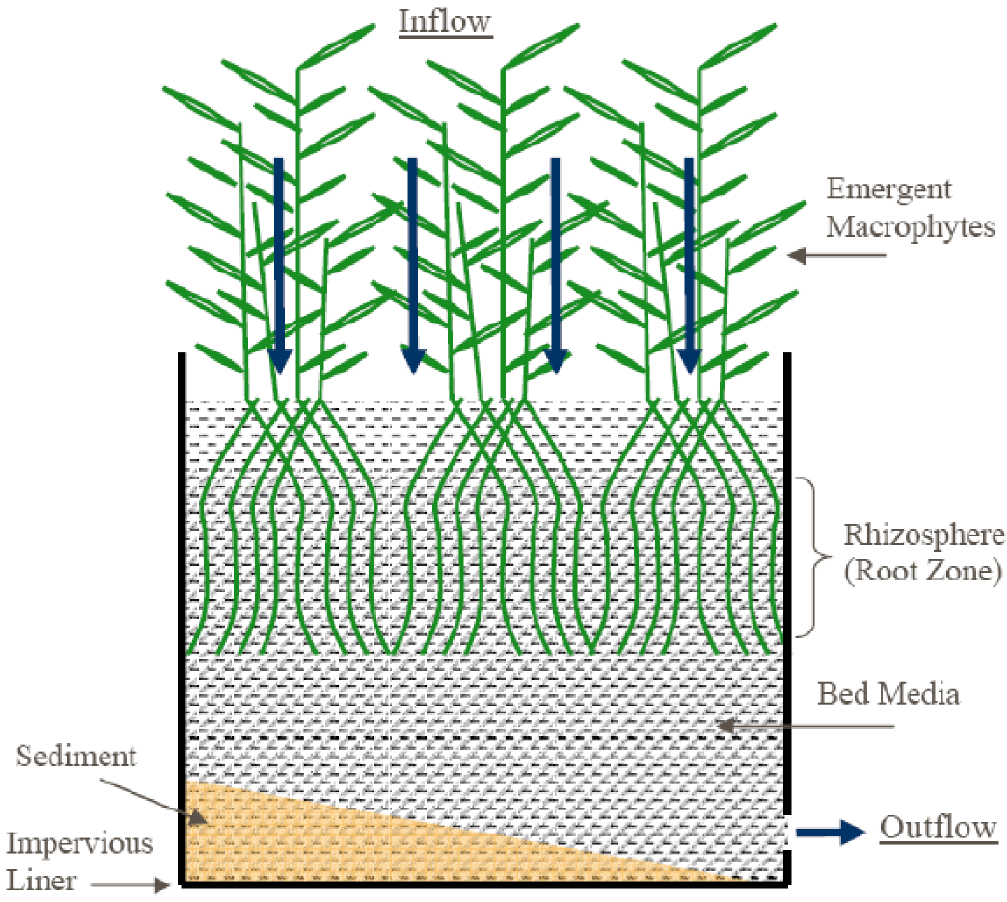


Figure 9: Vertical sub-surface flow helophyte filter (Weber, 2016)

3.2.2 How are helophyte filters made?

Consideration beforehand

When designing a helophyte filter, it is important to design a filter that is suitable for the type of wastewater that needs to be treated. The aforementioned types of filters and the size, are key aspects in designing an appropriate helophyte filter. Another important factor in the design are the available means, such as funds and area size (Kassa, 2019). Furthermore, the performance of a constructed wetland is dependent on factors such as: water depth, hydraulic retention time (HRT) and pollutant load, which can change over time (Gorgoglione & Torretta, 2018). This increases the difficulty of designing appropriate helophyte filters. Moreover, multiple pollutant removal processes, as described in chapter 3.1.2, are influenced by environmental conditions both in- and outside of the helophyte filter. These environmental conditions that can affect constructed wetland performance are: availability of organic carbon sources and dissolved oxygen, pH, temperature, redox conditions and operation strategies (Gorgoglione & Torretta, 2018). These factors all contribute to the wide variety of helophyte filters in use today.

Basic design

The basic design of all helophyte filters consists out of a basin, or waterbed, through which the water flows from one side to the other. Along the way, the water comes into contact with the macrophytes that are present, their microbiome and the substrate that is used. In Table 5, commonly used substrates for constructed wetlands are listed. The chosen material can have a strong influence on the hydraulic conductivity. In order to make the basin or channel impermeable, materials such as clay or geo-textile are used. This is then (partly) covered with rocks, gravel and soil, in which the chosen vegetation can be planted. When choosing the type of vegetation; the used substrate and environmental conditions should be taken into account (Economopoulou & Tsihrintzis, 2004). Important for consideration is the water flow through the filter; the HRT (hydraulic retention time). The water must go fast enough for the new influx to have room, but slow enough to allow contact with the microbiome and plants that will filter the water. (Vymazal & Kröpfelová, 2008; Stottmeister, et al., 2003)

The size of a constructed wetland is estimated on the basis of the pollutant removal theory. This is a theory consisting of multiple equations that calculate the needed removal rates of multiple pollutants that are common. As improving the water quality is the ultimate goal of helophyte filters, multiple standardized tests are commonly used in Europe and the USA. Based on these test results, filters can be adjusted to reach the sufficient level of cleaning. In most cases, it is a process of trial and error to get the optimal results (Economopoulou & Tsihrintzis, 2004; Nanninga, 2011). More information about commonly used indicators for the level of pollution, and equations that estimate the removal rates of BOD/COD, nitrogen and phosphorus can be found in Appendix A. Indicators for the level of pollutants and equations

Table 5: Commonly selected substrates for constructed wetlands (Gorgoglione & Torretta, 2018)

Type of substrate		
Natural material	**Industrial by-product**	**Synthetic products**
Sand	Slag	Activated carbon
Gavel	Fly ash	Lightweight aggregates
Clay	Coal cinder	Compost
Calcite	Alum sludge	Calcium silicate hydrate
Marble	Hollow brick crumbs	ceramsite
Shell	Moleanos limestone	
Limestone	Wollastonite tailings	

3.2.3 Current applications of helophyte filters

During the last decades, the multiple functions and values of wetlands have been recognized and exploited in the form of constructed wetlands. However, the use of wetlands for the improvement of water quality is not a new invention. For as long as humans have had wastewater discharges such as sewage, wetlands have more or less intentionally been involved in cleaning it (Carvalho, Arias, & Brix, 2017). This is due to the fact that wastewater is usually discharged, directly or indirectly, into ditches in the landscape, in which a wetland can form. Even today the discharge of wastewater into ditches is still common. Although the concept is very old, the term constructed wetland or helophyte filter is rather new (Brix, 1994a).

Types of wastewaters and their treatment

Currently, the number of application areas for helophyte filter technology has significantly expanded. (Wu, et al., 2015). During the start of the technological development, virtually all emphasis was on treating municipal wastewater. However, these past decades have shown a branching that includes a broad spectrum of wastewaters (IWA, 2000). For example, constructed wetlands have been used to purify agricultural and industrial effluents, mine drainage, landfill leachates, polluted river and lake water, urban and highway runoff, and storm sewage (Gorgoglione & Torretta, 2018). In addition, helophyte filters are a promising alternative for the treatment of wastewater in developing countries. In China for example, thousands of constructed wetlands have already been applied (Wu, et al., 2015). The following paragraphs will elaborate on some of the application areas.

Municipal wastewater

Municipal wastewater is mostly treated with a horizontal sub-surface flow system. These can be used to treat single houses and households, or even clusters of houses or an entire community (Gorgoglione & Torretta, 2018).

Industrial wastewater

There is a variety of industrial wastewater that has been treated by constructed wetlands. In Gorgoglione & Torretta's (2018) article on constructed wetlands, there is a classification made for industrial wastewater based on the industrial processes used: petrochemical and chemical industries, pulp and paper, textile and tannery industries, abattoir and meat processing effluents, food processing, and wineries and distilleries are wastewater producers of which the wastewater has been successfully treated. Mostly with the use of HSSF constructed wetlands (Gorgoglione & Torretta, 2018).

Agricultural wastewater

Agricultural wastewater, such as water from feedlot operations, is commonly treated with a FWS system, in which a series of lagoons are used as a step to pre-treat the wastewater (Gorgoglione & Torretta, 2018). These systems can successfully manage various pollutants, but only operate efficiently when the system has stabilized, which can take a few years (Dal Ferro, Ibrahim, & Borin, 2018).

Stormwater runoff

Stormwater mostly consists of agricultural and urban runoff and can be a great threat to the quality of surface waters (Li, Zhang, & Wang, 2017). It has been identified as one of the largest contributors to water pollution, with a large variety of contaminants. For the treatment of stormwater runoff, FWS filters are most commonly used, but other systems also have proved effective (Gorgoglione & Torretta, 2018).

Further applications

The main goal of helophyte filters will always be the purification of water. However, helophyte filters could also be used for water retention, recreation and the increase of biodiversity.

Water retention

The global trend in massive urban development comes with an increase of paved and impermeable areas in city centres. This reduction of green areas has increasingly altered the hydrological cycle, and creates challenges for the drainage of wastewater and rainwater in existing sewer systems. The most challenging problems are urban flooding and the urban heat-island effect. Existing drainage systems usually focus on feeding the water into existing sewer systems and wastewater treatment plants, but this can lead to temporary overloading and therefore flooding (Dou, Troesch, Petitjean, Gábor, & Esser, 2017). Helophyte filter mats are an innovative solution that could be used as a method of rainwater retention and the treatment of domestic wastewater, on the rooftops of buildings. The root zone of the helophytes delays and reduces the flow of rainwater, and the biology of helophytes makes them particularly attractive as they evapotranspirate much more water than terrestrial plants. By supplying the helophyte mats with wastewater from the household, the plants will have a permanent supply of water and nutrients, even during periods without rain, while effectively cleaning the water. (Zehnsdorf, Blumberg, & Müller, 2018)

Recreation

Besides being an attractive form of treating wastewater, helophyte filters could also have a recreational purpose. Keeping in mind that recreation could also damage the helophyte systems, if properly managed and planned, constructed wetlands could have educational purposes, allow for recreational harvest, as well as a place for exercise activities (Rousseau, Lesage, Story, Vanrolleghem, & De Pauw, 2008). In a scientific article written by Nyakang'o and van Bruggen in 1999, a constructed wetland was built in Nairobi that could provide an aesthetically pleasing and environmentally sensitive landscape for recreation. The wetland is used to treat the wastewater of a restaurant and a swimming pool resort and is filled with indigenous reeds, like *Cyperus alternifolius, Cyperus latifolius* and ornamental plants such as *Arundo donax varigata, Pontederia* and *Sagittaria*, and wild flowers like *Ajuga remota* and *Aspilia mossambicensis* (Nyakang'o & van Bruggen, 1999). Since then, more helophyte filter projects that also serve as a recreational facility have been built. For example, The Lankheet Waterpark at Haaksbergen, is created with a series of different objectives including reed production for biomass, water purification, anti-desiccation, water storage and recreation (de Blaeij & Reinhard, 2008). Figure 10 shows a constructed wetland as a swimming pond.

Figure 10: Swimming pond with water purifying qualities (Weijer, 2021)

Biodiversity

Wetlands are well known as rich and biodiverse ecosystems where countless species of amphibians, birds, fishes, invertebrates, mammals, and reptiles thrive. Multiple studies have shown that constructed wetlands can increase biodiversity, especially when designed and managed properly (Hsu, et al., 2011). Different types of plants can occur in the basin or around the system, and the helophytes could provide habitat and food for all kinds of organisms. For example, in a study of Rodrigo *et al*. (2018) constructed wetland systems were recommended in the management of eutrophicated waters and for the enhancement of waterfowl species that are of conservation concern.

3.3 Which edible plant species can be used in a helophyte filter, and what should be considered regarding the use of these species?

This chapter explores a vast number of plant species that are currently used in helophyte filters and lists their edibility. A few examples of interesting edible plants will be elaborated upon. Furthermore, some information is given about what needs to be considered when using helophyte filters as a food source.

3.3.1 Which plant species are currently used?

Selection of the macrophytes

When selecting the appropriate macrophyte species, a number of factors should be considered. These factors include: the climate conditions of the site, the characteristics of the wastewater that needs treatment and the effluent quality (Gorgoglione & Torretta, 2018). Furthermore, the most suited species can be chosen by looking at the plants adaptability to the saturation conditions of the soil, the growth potential of the roots and their oxygen carrying capacity, the photosynthetic efficiency and tolerance to high concentrations of pollutants, their disease resistance, and the required management (Gorgoglione & Torretta, 2018). However, the aim of this report is to add a sub-function to helophyte filters by opting for helophytes that are edible. Thus creating a filter for wastewater that can also serve as a food source.

A vast amount of plant species are used in helophyte filter systems worldwide. As mentioned before, constructed wetlands are not exclusively built with helophytes. The macrophytes include emergent plants, submerged plants, floating-leaved plants and free-floating plants. **Fout! Ongeldige bladwijzerverwijzing.**, displayed at the end of chapter 3.3.3, shows all the specific plant species that were listed in the literature on constructed wetlands, used for this report. However, this is only a selection of the plants that can be found in all the different types of filters and countries around the world. The macrophytes are sorted by their family and for each plant species, the Latin and English name is indicated, as well as the edibility of the plant. This list establishes that many plants that are already used in helophyte filters have the potential to be used as a food source.

The most common plant used in helophyte systems in Europe, and also across Asia, is the emergent macrophyte *Phragmites australis* or common reed (Almuktar, Abed, & Scholz, 2018). In North America, *Typha latifolia* (common bulrush) is most frequently utilized. And the species *Cyperus papyrus*, or papyrus sedge, is most common in Africa. In Central and South America, as well as Oceania, *P. australis, T. domingensis* (southern cattail) and *Scirpus lacustris* (common clubrush) are the most popular plants (Almuktar, Abed, & Scholz, 2018).

When taking a closer look at **Fout! Ongeldige bladwijzerverwijzing.**, it is evident that the species most frequently used are plants from the families: Araceae, Cyperaceae, Hydrocharitaceae, Poaceae and Typhaceae. Except for the species in the Hydrocharitaceae family, most of these plants are quite edible.

Uses besides edibility

Constructed wetlands can offer many other uses apart from filtering water or their edibility. *P. australis* for example, has been used by humans for centuries for a wide range of applications (Wichmann & Köbbing, 2015). In Europe its most common use is as roofing material, as shown in the thatched roof in Figure 11. And since common reed is already the most used macrophyte species in Europe, its harvest could make a profitable commodity for thatching companies. In the next chapter, some edible species listed in **Fout! Ongeldige bladwijzerverwijzing.** will be elaborated upon. This will include their uses besides edibility and medicinal properties mentioned in PFAF (2020). Furthermore, the macrophytes used in helophyte filters could also be chosen for their decorative potential. A literature survey on the ornamental possibilities of 87 constructed wetlands from 21 countries by Sandoval in 2019, showed that the four most commonly used ornamental plant genera were: *Canna, Iris, Heliconia* and *Zantedeschia.* This rapport states that ornamental flowering plants are an excellent option in helophyte filters. They can be just as effective as typical wetland plants, and can add more esthetic to the system. By adding a harvesting regime to these ornamental helophytes, they could also be made profitable.

Figure 11: Roof thatching with common reed (P. australis) (Fewins, 2000)

3.3.2 Edible species

Phragmites australis

Common reed (*P. australis*) is the most famously used helophyte in constructed wetlands where it has been used in each of the different filtration systems (Gorgoglione & Torretta, 2018). The species is an emergent perennial from the Poaceae family and is one of the most substantially distributed species of emergent macrophyte worldwide. Moreover, it can inhabit both aquatic and terrestrial ecosystems, and is widespread along temperate and tropical regions around the world. For many years, this plant has been used in the purification of various types of wastewater, because of its ability to accumulate numerous micropollutants, nutrients and heavy metals (Milke, Gałczyńska, & Wróbel, 2020). The species can be recognized by its cane-like stem that can grow relatively high (up to 6 metres tall), compared to other emergent aquatic species (see Figure 12). Above-ground biomass could be harvest once a year in wintertime to minimise conflict with nature conservation (e.g. breeding birds), or in summer time to provide biomass with higher nutrient content, more suitable for consumption (Köbbing, Thevs, & Zerbe, 2013).

Common reed has been utilized by man since ancient times. For centuries the species has been used as animal fodder in summer, and for craft and construction material making in winter time. There is evidence of reed thatched roofs as early as the last ice age, which is still a common practice (Köbbing, Thevs, & Zerbe, 2013). It has also been utilized for fences, indoor furniture, floors, walls, insulation, and many more uses. Nowadays, reed biomass is often used as an energy source, namely by biogas and biofuel production. Furthermore, common reed has a lot of nutritional value with high contents of nitrogen, potassium and manganese, which makes it a good fodder plant for ruminants. There have also been some reports on human consumption, especially in Asia and Native America, where the roots and seed were eaten. But this is not common practice. However, the roots, young shoots, seed, inside of stem and an extract from stalks or wounded stems have all been proven to be edible for human consumption (Köbbing, Thevs, & Zerbe, 2013).

There are also some medicinal uses attributed to the common reed. For example, the leaves have been used in the treatment of bronchitis and cholera. A decoction of the flowers has also been used to treat cholera as well as food poisoning. The root can be ingested in the treatment of diarrhoea, heavy coughing, fevers, food poisoning, lung abscesses, urinary tract infections and vomiting (PFAF, 2020).

Figure 12: Phragmites australis (Banda, 2019)

Typha latifolia

The common bulrush (*T. latifolia*) is a wetland species that can be found in most parts of the Northern Hemispheres, where it grows in a variety of climates. This emergent macrophyte, and others of its family (Typhaceae), are frequently used in helophyte filters for the treatment of wastewater (Gorgoglione & Torretta, 2018). Together with *P. phragmites*, it is one of the most effective wastewater cleaning macrophytes, and able to absorb significant amounts of carbon, nitrogen, phosphorus, potassium and heavy metals (Geurts, et al., 2020). The common bulrush can grow to be 2.5 meter tall and is a productive species with a high above-ground biomass (Rana & Maiti, 2018). The plant has long and thick leaves that are flat and pointed, and is most noticeable characteristic is its cigar-like female flowerhead (shown in Figure 13). At the end of each vegetative cycle, the plants should be harvested to obtain the most effective removal of pollutants (Ciria, Solano, & Soriano, 2005).

Harvested material of the common bulrush has already been transformed into animal feed, compost, fertilizer and raw material for the paper industry (Ciria, Solano, & Soriano, 2005). There are also many edible uses ascribed to *T. latifolia*. The roots of the common bulrush are most known for their edibility. They can be eaten like potatoes after peeling and cooking. Roots can also be dried and ground into a protein rich powder, used for baking (e.g. bread, biscuits). The young shoots can be eaten in spring as an asparagus substitute and are known to taste like cucumber. Also the base of the mature stem (with the outer part removed), the immature flowering spike that tastes like sweet corn and the seed, are edible. The seeds can be roasted for a pleasant nutty taste or ground into flour for baking; the pollen is also edible and can be added to flour as a protein rich additive. Additionally, the young shoots, the base of the mature stem (with the outer part removed), the immature flowering spike, seed and the pollen are also edible (PFAF, 2020).

Typha latifolia also has a litany of medicinal applications. The leaves have been mixed with oil to use as a poultice on sores. Dried pollen is said to be a blood thinner, but also a blood thickener when roasted with charcoal. Common bulrush could be used internally to treat abnormal uterine bleeding, abscesses, cancer of the lymphatic system, haemorrhage, kidney stones, painful menstruation and post-partum pains. However, it should not be prescribed for pregnant woman. The plant has been used externally to treat diarrhoea, injuries and tapeworms. Furthermore, roots have been used in poultices to treat boils, burns, cuts, inflammations, scalds and sores, and the flowers in treatments including abdominal pain, cystitis, dysuria and vaginitis (PFAF, 2020).

Figure 13: Typha latifolia (Boyt, 2009)

Lemna minor

Duckweed (*L. minor*) is a promising edible species for water filtration from the Araceae family that has already drawn a lot of attention worldwide (Liu, Xu, Yu, & Zhou, 2020). Duckweed are small floating macrophytes that can occur in small waterbodies (Figure 14). They are distributed world-wide and are among the fastest growing plants in the world, able to double its biomass every 48-96 hours. However, they play a less direct role in the treatment of wastewater compared to helophytes. This is due to their lack of an extensive root system, which only allows for a small amount of bacterial attachment. A dense cover of this species in a helophyte system would largely inhibit the amount of oxygen available in the system, creating a largely anoxic environment that would in turn allow for a lot of denitrification. Frequent harvest of the biomass would remove the nitrogen taken up by the plants and is essential in order to maintain a high growth rate (and nutrient uptake). This would also ensure that the nutrients the plants have taken up, will not be released back into the water once decomposition starts (Vymazal & Kröpfelová, 2008 (a)). Moreover, reports suggest a harvesting regime of once or twice a week, which would only differ in the amount of biomass harvested.

Duckweed is a rich source of proteins and amino acids. It also contains many vitamins and carotenoids as well as macro- and micronutrients (Sońta, Rekiel, & Batorska, 2019). Duckweed has already been widely used in animal feed and aquaculture production, where it has been proven to be successful. Besides being used as animal feed, duckweed could potentially also be used for human consumption. A research on the cytotoxic effects of several duckweed species has concluded that it is safe for human consumption and that it is 100% edible (Liu, Xu, Yu, & Zhou, 2020).

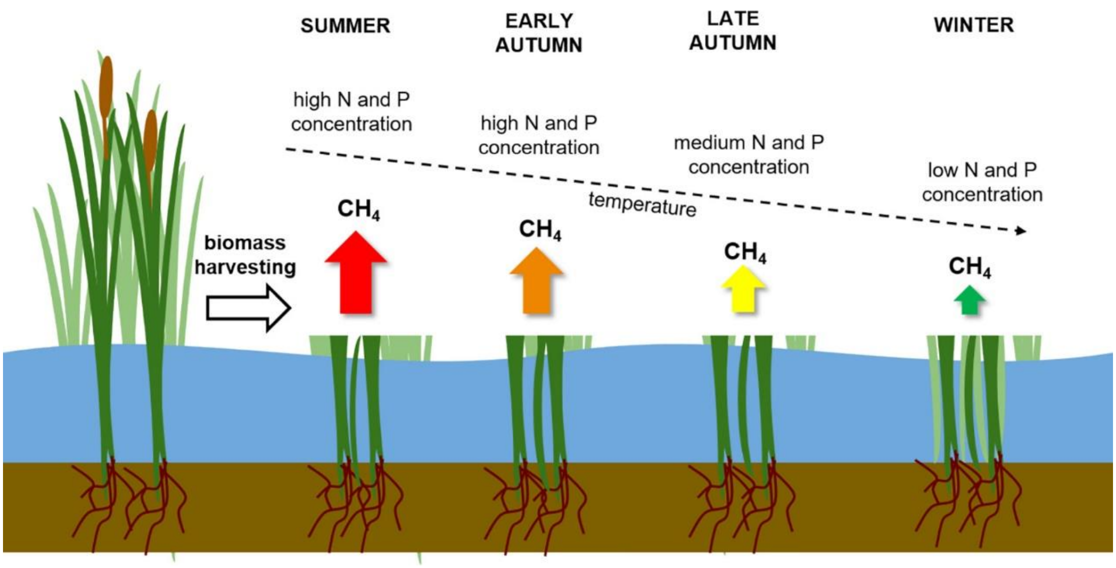
The plant species also has some medical uses. It has been used in the treatment of colds, oedema, measles and with urination difficulties. Duckweed has also been applied on the skin, in the treatment of skin diseases, and used as a wash for eye inflammation (PFAF, 2020).

Figure 14: Lemna minor (Cameron, 2021)

3.3.3 Considerations

Harvesting regime

The concept behind constructed wetlands is that plants incorporate the nutrients of the wastewater into their tissue during the growing season, which subsequently could be harvested (Verhofstad, Poelen, van Kempen, Bakker, & Smolders, 2017). In order to improve the long-term performance of constructed wetlands, sustainable operation strategies, such as plant harvesting regimes, have been proposed. However, there has been much debate about the benefits of these regimes. Several studies have argued that plant harvesting might alter the interactions between the plants and the micro-organisms living in their rhizosphere. In a study of Zheng et al. (2018), the difference between harvested constructed wetlands in contrast to non-harvested constructed wetlands was examined using common reed. They concluded that long-term plant harvesting enhances CW performance by improving the biomass, density, and nutrient uptake. They also found that harvesting strengthens the diversity and richness of the microbial community significantly, which would in turn enhance carbon and nitrogen cycling. Evidently, the nutrient removal efficiency of CW's with a harvesting regime can certainly be higher than that in an unharvested constructed wetland (Zheng, et al., 2018). However, Kasak, et al. (2020), mentions the importance of strategic planning of the harvest. Harvesting the biomass in the summer will maximize the amount of nutrients removed from the system, but also produces large methane fluxes that escape into the atmosphere from the plant tissues. Their study suggests that the optimal time for above-ground biomass harvesting is at the end of the growth season in late September. As shown in



enough

Figure 15: The timing of biomass harvest and the coinciding N and P concentration and greenhouse gas emission (Kasak, et al., 2020)

Furthermore, it is important to do a lot of thorough research before deciding to harvest and eat species from a helophyte filter system. Specific plant parts may need to be prepared in a specific way to prevent toxicity (e.g. cooking), and for many species, research on their suitability for human consumption is either minimal or incomplete (PFAF, 2020). Moreover, of many species listed in **Fout! Ongeldige bladwijzerverwijzing.**, the roots are edible, but most harvesting consists of removing the above-ground biomass. Harvesting the roots might harm the helophyte filter, or could prevent the plants from growing back properly (Vymazal, 2020; Verhofstad, et al., 2017). Plant species grown in helophyte filters could also potentially be harvested for the medicinal uses that they offer.

Table 6: Plant species used in constructed wetlands and their edibility (PFAF, 2020)

Selection of plant species used in constructed wetlands

Family	Scientific name	English name	Edible?	Which part?
Acoraceae	*Acorus calamus*	Sweet flag	YES	Leaves, roots and stem. Caution advised with the roots.
Alismataceae	*Alisma plantago*	Common water plantain	YES	Leaves and roots. Caution is advised.
	Alisma triviale	Northern water plantain	YES	Bulbous base
	Sagittaria latifolia	Broadleaf arrowhead	YES	Roots
Araceae	*Lemna gibba*	Gibbous duckweed	YES	Whole plant
	Lemna minor	Common duckweed	YES	Whole plant
	Lemna trisulca	Star duckweed	NO	
	Lemna minuta	Least duckweed	NO	
	Pistia stratiotes	Water lettuce	YES	Young leaves
	Spirodela polyrhiza	Great duckweed	YES	Leaves
	Spirodela punctata	Dotted duckweed	NO	
	Wolffia columbiana	Columbian watermeal	YES	Leaves
Araliaceae	*Hydrocotyle umbellata*	Dollarweed	YES	Leaves
Cabombaceae	*Cabomba caroliniana*	Carolina fanwort	NO	
Cannaceae	*Canna indica*	Indian shot	YES	Roots
Ceratophyllaceae	*Ceratophyllum demersum*	Coontail	MAYBE	Leaves are listed as edible, but not enough information available.
Convolvulaceae	*Ipomoea aquatica*	Water spinach	YES	Leaves, roots and shoots
Cyperaceae	*Baumea articulata*	Jointed twig rush	NO	
	Carex acutiformis	Lesser pond sedge	YES	Roots
	Carex aquatilis	Water sedge	YES	Roots and seed
	Carex lacustris	Lake sedge	YES	Roots and seed
	Carex stricta	Tussock sedge	YES	Roots and seed
	Carex rostrata	Bottle sedge	YES	Roots and seed
	Cyperus papyrus	Papyrus sedge	YES	Roots and stem
	Cyperus involucratus	Umbrella plant	NO	
	Eleocharis acicularis	Needle spikerush	NO	
	Eleocharis acuta	Common spikerush	YES	Roots
	Eleocharis dulcis	Chinese water chestnut	YES	Roots and corm

	Eleocharis macrostachya	Pale spikerush	NO	
	Eleocharis sphacelata	Tall spikerush	NO	
	Scirpus acutus	Hardstem bulrush	YES	Leaves, pollen, roots and seed
	Scirpus californicus	California bulrush	YES	Rhizomes and stem
	Scirpus fluviatilis	River bulrush	YES	Roots and stem
	Scirpus lacustris	Common clubrush	YES	Leaves, roots, pollen, seed and stem
	Scirpus maritimus	Seaside bulrush	YES	Roots and seed
	Scirpus validus	River clubrush	YES	Leaves, pollen, young roots and shoots
Haloragaceae	*Myriophyllum aquaticum*	Parrot's feather	YES	Leaves
	Myriophyllum heterophyllum	Veriableleaf watermilfoil	NO	
	Myriophyllum spicatum	Eurasian watermilfoil	YES	Roots
	Myriophyllum verticillatum	Whorl-leaf watermilfoil	YES	leaves
Hydrocharitaceae	*Egeria densa*	Brazilian waterweed	NO	
	Elodea canadensis	Canadian waterweed	NO	
	Elodea nuttallii	Nuttall waterweed	NO	
	Hydrilla verticillate	Waterthyme	NO	
	Hydrocharis dubia	Frogbit	YES	Young flowers
	Hydrocharis morsus-ranae	Common frogbit	NO	
	Najas guadalupensis	Southern waternymph	NO	
	Vallisneria americana	Eelgrass	YES	Young leaves
Iridaceae	*Iris pseudacorus*	Yellow flag	MAYBE	Seed
	Iris versicolor	Blue flag	NO	
Juncaceae	*Juncus articulatus*	Jointleaf rush	NO	
	Juncus balticus	Baltic rush	YES	Seed and sugary substance from the top of the plant
	Juncus effusus	Soft rush	YES	Young shoots, caution advised
	Juncus subulatus	Somerset rush	NO	
Lamiaceae	*Mentha aquatica*	Water mint	YES	Leaves
Lythraceae	*Lythrum salicaria*	Purple loosetrife	YES	Leaves, roots and edible dye from the flowers
	Trapa bispinosa	Water caltrop	YES	Seed
Marsileaceae	*Marsilea quadrifolia*	European waterclover	MAYBE	Young stem and leaves
Menyanthaceae	*Nymphoides peltata*	Water fringe	YES	Leaves, leaf stems and flower buds
Nelumbonaceae	*Nelumbo nucifera*	Sacred lotus	YES	Flowers, leaves, roots, seed, stem and stamens
Nymphaeaceae	*Nuphar lutea*	Yellow waterlily	YES	Leaves, roots, seed and flowers
	Nymphaea tetragona	Pygmy waterlily	MAYBE	Roots are listed as edible, but not enough information available
Poaceae	*Echinochloa pyramidalis*	Antelope grass	YES	Leaves, stem
	Glyceria maxima	Reed sweet-grass	YES	Leaves, stem
	Pennisetum purpureum	Napier grass	YES	Flowers, young shoots and leaves, stem
	Phalaris arundinacea	Canary grass	NO	

	Phragmites australis	Common reed	YES	Roots, young shoots, seed, inside of stem, extract from stalks or wounded stems
	Phragmites karka	Tall reed	YES	Young shoots
	Poa palustris	Fowl blue grass	NO	
	Vetiveria zizanioides	Vetivergrass	YES	Roots
	Zizania latifolia	Manchurian wild rice	YES	Young flowers and shoots, roots, seed, stem
Pontederiaceae	*Eichhornia crassipes*	Water hyacinth	YES	Young leaves, petioles, flower spikes
	Potenderia cordata	Pickerelweed	NO	
Potamogetonaceae	*Potamogeton crispus*	Curled pondweed	YES	Young leaves
	Potamogeton pectinatus	Sago pondweed	YES	Leaves, roots and stem
	Potamogeton perfoliatus	Clasping-leaved pondweed	YES	Leaves, roots and stem
Ruppiaceae	*Rupia maritima*	Beaked tasselweed	NO	
Salviniaceae	*Salvinia molesta*	Giant salvinia	NO	
	Salvinia natans	Floating fern	NO	
Sparganiaceae	*Sparganium erectum*	Burr-reed	YES	Roots and stem base
Typhaceae	*Typha angustifolia*	Lesser Bulrush	YES	Roots, young shoots, base of mature stem (outer part removed), young flowering stem, pollen, seed
	Typha domingensis	Southern cattail	YES	Flowers, leaves, young shoots, base of mature stem and young flowering stem, seed, pollen and roots
	Typha glauca	Hybrid bulrush	YES	Flowers, leaves, pollen, roots, seed, stem and an edible oil from the seed
	Typha latifolia	Common bulrush	YES	Roots, young shoots, base of mature stem (outer part removed), immature flowering spike, seed and pollen
	Typha orientalis	Asian bulrush	YES	Flowers, leaves, pollen, roots, seed and stem

4 Discussion

In this chapter, a critical look is given to the research methodology and results of this report. Beforehand, it is important to acknowledge that helophyte filters are not always the best choice for water purification. In some cases the pollutants in wastewater can be so specific or at such high levels that plants are insufficient to clean them (Stottmeister, et al., 2003). Moreover, some types of helophyte filters need a significant amount of resources or management to function properly (Nanninga, 2011), which might not be available. Nevertheless, in many cases, helophyte filters are a sustainable method of water filtration with multiple benefits compared to conventional wastewater treatment systems. Adding the function of food production to these filters would increase the value of helophyte filtration systems.

4.1 Method used to find and judge information

As described in chapter 2, a clear method for finding credible sources was used. This literary study combines information acquired from over 60 sources. Most of the referenced sources are reports found in scientific journals, however, unpublished reports, governmental work and some books, were also used. This wide base of sources lends strength to the results described in this report, as the sources validate each other. Because the main goal of this report was the relatively novel idea of harvesting edible plants from helophyte filters, only a few sources were found that specifically focus on this topic. However, sources regarding different topics around helophyte filters still offered useful information.

A critique on the sources used is that many state similar information. As such the amount of sources used could have been lowered, making for a more concentrated base. Furthermore, the sources used to write chapter 3.2.1 will not provide a complete overview of all the different helophyte systems available around the world. With such high variability in helophyte filters it is not always clear how inclusive sources are, or which ones are most accurate. With topics such as the biology of aquatic macrophytes, or the functioning of helophyte filters, this wide variety of sources is less of a problem, as the subject's function is generally the same. In future research, a smaller field could be focused on to avoid this problem, by for example; focussing on a specific climate, country or type of helophyte filter.

4.2 Results

The first two sub-questions of this research focusses on the current understanding of helophyte filters by looking at how this system works and what types of filters are in use. While the last sub-question focuses on the possible use of edible plants to further improve helophyte filters. For every sub-question a critical look of the results is presented below.

4.2.1 How does a helophyte filter work?

The first sub-question focusses on the biology of aquatic macrophytes and the processes that filter pollutants. The biology and evolutionary adaptations of macrophytes are well studied and documented. Our current understanding of them is described in this report based on a number of articles published in the last 30 years. This wide time span can be an issue for some topics, but in the case of aquatic macrophytes it rather shows that our knowledge on them is well established. The information on the different pollutants and processes in place for cleaning them is mainly based on basic principles of biology, chemistry and physics, which are universally true and accepted. Only common pollutants and their removal are described in this report because these pollutants are considered for the average helophyte filter (Economopoulou & Tsihrintzis, 2004). However, depending on the situation a new helophyte filter is built for other types of pollutants can be of great importance to the design, an example of this are pharmaceutical compounds that can be found in municipal wastewaters. In these cases components such as special substrate or plants are added to filter out these pollutants (Zhang et al., 2011). Such cases have not be described in this report to keep the information on these topics concise.

4.2.2 What types of helophyte filters are there?

The types helophyte filters, described in sub-question 2, have specific attributes to divide them by. In practicality with the many helophyte filters used globally, these types might blend in to each other and have less clear divisions. Some filters can be categorized in one type, which than has even more sub-categories (Environmental Pollution, 2008). To keep the information presented incisive, the main types of filters and their attributes used in literature have been described. This report focusses mainly on the plants used in filters while types of wastewater are mainly summarized. In future research it might be interesting to explore the differences between different types of wastewater to greater extent. Municipal water could be highly different from country to country or even from city to city. The same holds true for wastewater produced by different industries. A better understanding of the wastewater can help design helophytes filters for greater efficacy and possibly a more suitable choice of edible helophyte use.

4.2.3 Which edible plant species can be used in a helophyte filter?

In the third sub-question a relatively new idea is explored; that of harvesting edible plants from helophyte filters. This idea is not completely new as some plants grown in helophyte filters are already harvested as resource for a variety of uses, however, is not very common. Although there are already edible plants in existing helophyte filters, to regularly harvest them would require clear harvesting regimes and people to implement these regimes. If too many plants are harvested there could be negative repercussions. A serious effort of the party in charge of the helophyte filter is needed to prevent such problems. Many sources already confirm that good management is key for the successful use of helophyte filters (Biswas & Tortajada, 2019; Rousseau, Lesage, Story, Vanrolleghem, & De Pauw, 2008). Moreover, small helophyte filters will not be eligible for the production of significant amounts of food or other resources. In helophyte filters designed with the production of food in mind, regularly harvesting might be paramount for the filter efficacy. Already existing helophyte filters would not suffer from irregular harvesting as this was not part of the original design (Zheng, et al., 2018).

5 Conclusion

In this closing chapter of the report, the main research question will be answered, using the information gained from the three sub-questions. The results, with regards to the critical look from the discussion, will be used to answer each question concisely.

5.1 How does a helophyte filter work?

Helophyte filters can purify water based on a combination of biological, chemical and physical processes that are induced by the interaction of plants, micro-organisms, the soil and pollutants. The main component of such filters are plants that have adapted to thrive in water-rich environments. These plants provide a beneficial environment for a range of micro-organisms in their rhizosphere. Both the plants and the micro-organism can purify the water, sequestering pollutants or degrading them to use as nutrients. Apart from organisms, physical components, like a settling tank and sediment filter, are important. Factors such as the hydraulic retention time, total area, and the rate with which the water is added to the system, can greatly influence the treatment efficiency. By designing a system optimal for the level of pollutants that need to be filtered an efficient helophyte filter can be made.

5.2 What types of helophyte filters are there?

Helophyte filters can be categorized according to the type of plants used, as well as the wastewater flow path. They are often classified into two types: free water surface and sub-surface flow, but there are also hybrid systems possible. The right choice between these filter types depends on the type of wastewater that needs to be filtered and the resources available. When designing or testing a helophyte filter, a few common pollutants are taken into account. Helophyte filters have already been applied on multiple types of wastewater, and also play a beneficial role in water-retention, recreation and biodiversity

5.3 Which edible plant species can be used in a helophyte filter, and what should be considered regarding the use of these species?

A wide variety of plants is used in helophyte filters all over the world, consisting of not only helophytes but also other aquatic macrophytes. When selecting the appropriate species, a number of factors should be considered to create an optimal system. Of the plants used in constructed wetlands, many already have edible parts, and apart from being used as a human food source, they can also serve for other uses. Three plants were researched and were found to be safe for human consumption, as well as having medicinal properties. In order to improve the long-term performance of constructed wetlands, plant harvesting regimes should be conducted. And by timing these strategically, the amount of greenhouse gas emission will be minimizes, while also maximising the amount of nutrients harvested. However, it is important to do a lot of research before deciding to harvest and eat species from a helophyte filter system.

5.4 What are the prospects of using helophyte filters as a food source?

The importance and use of helophyte filters have long been proven. In recent years helophyte filter technologies are being expanded to treat more types of wastewater. This report gives an overview on the current state of helophyte filters and provide the reader with ideas to further improve helophyte filters by adding in food production. Many existing helophyte filters already consist of a large number of edible plants. However, these are not yet harvested for human consumption. By making use of an optimal harvesting regime, the harvested biomass can be nutrient-rich while also minimizing greenhouse gas emissions. Before harvesting and eating plants from a helophyte filter system, sufficient research is needed. Some plant parts might need to be prepared in a specific way to prevent toxicity, and improper harvesting might harm the helophyte filter. As this report shows helophyte filters have the potential to be more than just a method of sustainable water filtration. Both future and current filters, globally in use, hold nutrient-rich and exciting food sources ready for the picking.

Appendices

Appendix A. Indicators for the level of pollutants and equations

Commonly used indicators for the level of pollution

To measure how polluted the water is, there are two equations that can calculate the BOD, COD, N-total or P-total values. BOD stands for; Biological Oxygen Demand, and COD for; Chemical Oxygen Demand. Both are a measure in the performance of micro-organisms (Economopoulou & Tsihrintzis, 2004). Micro-organisms use dissolved oxygen to break down organic compounds. Therefore, measuring the amount of oxygen needed to clean the water is an indicator of how polluted the water is (Metcalf & Eddy, Inc., 2004). The BOD test measures three types of reactions over time, which usually takes 5 days (BOD_5) (Nanninga, 2011). The aerobic biological degradation consists of three reactions, and the measured BOD value is the amount of dissolved oxygen that is needed to complete these reactions (Metcalf & Eddy, Inc., 2004). COD tests only take about 2,5 hours and use dichromate in an acid solution to measure the dissolved oxygen. Both BOD and COD should give the same value, but this is rarely the case. This is because biological reactions cannot dissolve the broad range of chemicals that can be present in the wastewater, and because micro-organisms die during this five-day period (Nanninga, 2011). The pollutants measured using the BOD and COD, are filtered throughout the helophyte filter. Higher oxygen levels (closer to the water surface) and higher water temperatures, catalyse these reactions. The N-total is the sum of the total nitrogen, including ammonia (organic and reduced nitrogen), nitrate (NO_3^-) and nitrite (NO_2^-). And P-total is the total amount of phosphorous with its organic and inorganic forms.

Furthermore, calculating the total suspended solids (TSS) is also a measure to examine the pollutant level. TSS are all the solids that can be found in the wastewater, as described in chapter 3.1.2. For testing TSS, a filter is used with pores varying from 0.45 µm to 2.0 µm (Metcalf & Eddy, Inc., 2004).

Equations

In constructed wetlands, the BOD/COD, nitrogen and phosphorus removal rates are estimated by the following general equations (1 - 4) (Reed, Crites, & Middlebrooks, 1995) (Kadlec & Knight, 1996).

$$\frac{C_e}{C_i} = e^{-K_T t} \qquad (1)$$

$$\frac{C_e}{C_i} = e^{-\frac{K_1}{h_1}} \qquad (2)$$

In these two general equations: C_e is the pollutant effluent concentration [mg L^{-1}] of BOD/COD, nitrogen or phosphorus. C_i is the pollutant influent concentration [mg L^{-1}] of BOD/COD, nitrogen or phosphorus. KT is a reaction rate parameter [d^{-1}] dependent on the water temperature T [°C] and t is the hydraulic residence time (HRT) in the system [d]. In general equation (2), the pollutant of interest: K1 is a reaction rate constant [m d^{-1}] dependent on the type of pollutant (Table 7) and hl is the hydraulic loading rate [m d^{-1}]; (Economopoulou & Tsihrintzis, 2004)

The parameters (hl) and (t) are defined by the following equations:

$$h_l = \frac{Q}{A} \qquad (3)$$

$$t = \frac{V}{Q} = \frac{A\,y\,\phi}{Q} = \frac{y\,\phi}{h_l} \qquad (4)$$

Q is the assumed constant of the design flow rate [m^3 d^{-1}]. A is the mean surface area of the system [m_2]. V is the system volume [m^3]. The y is the flow depth [m]. And ϕ is the fractional porosity, that expresses the space availability for water to flow through vegetation and litter present in a FWS constructed wetland system (Reed, Crites, & Middlebrooks, 1995). By taking into account the amount of pollutants that need to be filtered, these equations can compute certain spatial measures such as; the surface area and the depth of the filter. Thereby helping with the initial design of the helophyte filters. Furthermore, extra factors can be added in these equations to make them more complex (Economopoulou & Tsihrintzis, 2004).

Based on the level of pollutants that can be calculated by these and similar equations, some countries have made legislation that assigns a certain quality label to a helophyte filter. In The Netherlands for example, the amount of pollutants that are acceptable in a 24-hour sample and therefore will receive the highest quality label are shown in Table 7. The effectiveness of the filter can be calculated by comparison of the influent and effluent. These formula's do not include micronutrients or heavy metals, which unfortunately could be an important factor in CW quality. (Nanninga, 2011)

Table 7: Legislation helophyte filer quality label; acceptable pollutant levels over an 24hour sample to gain the highest quality label (IBA Class IIIB) in the Netherlands

Units		Concentration
BOD_5	mg/l	20.0
COD	mg/l	100
NH_4^+	mg/l	2.00
P-total	mg/l	3.00
TSS	mg/l	30.0

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