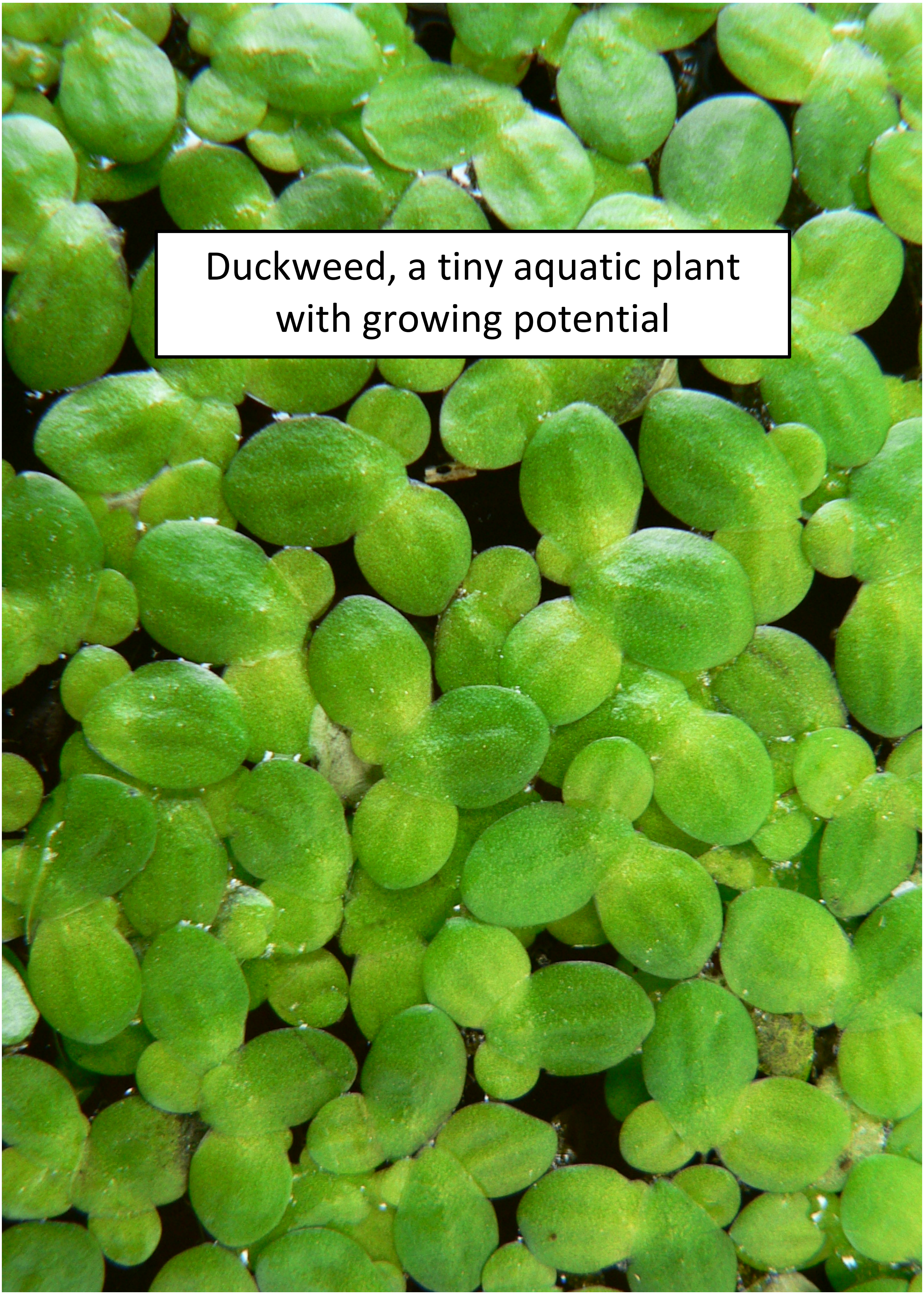
Duckweed, a tiny aquatic plant with growing potential



Duckweed, a tiny aquatic plant with growing potential

A research on the potential applications of duckweed in urban water systems in The Netherlands

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Summary

This paper evaluates the potential application of duckweed found in urban waters. This research is executed by seven master students of Utrecht University in commission of water research institute KWR and the water board of Delfland. Research is conducted by means of literature review and complemented by expert interviews. In urban waters, intense duckweed cover causes problems concerning odor, aesthetics and ecological water quality. Citizens complain to the local water authority and municipality about the odor, and the Dutch government is responsible for good ecological quality of the water. Therefore solutions need to be brought up on how to cope with unwanted duckweed growth. The best solution would be to transform the duckweed from waste into a valuable product and subsequently incorporate this product into the market.

There are two basic ways to deal with the problems caused by duckweed: prevention and collection. Whether duckweed should be prevented or collected depends on the specifics of water bodies, quality of the duckweed, and needs of the local authority. To prevent duckweed several approaches can be considered. The most useful prevention method consists of lowering the nutrient level in a water body, which can be achieved by dredging the nutrient rich sediment layers. However, the initial implementation costs for dredging are high. In order for nutrient reduction to be a sustainable and structural solution, inputs of nutrients also need to be halted. Reducing nutrient concentration serves a wider societal goal, and hence the costs could be spread over multiple fields of interest (the goal of overall ecological water quality improvement). Another interesting prevention method for duckweed is to increase the flow velocity to the flush the duckweed away. Moreover, duckweed cannot grow in fast flowing waters. This can be implemented by pumping or the installation of small weirs. If such an artificial water management system is present, or when it can be relatively easy installed, this method has lower costs than dredging.

The most suitable collection methods include duckweed screens and other manual collection methods, due to their high efficiency and relatively low costs. On the other hand, on the long term these manual collection methods will probably be more expensive than, for example, the Proskim water skimmer or the Duckweed Guzzler. This is because the Proskim water skimmer and the Duckweed Guzzler are both methods with high initial implementation costs, but low maintenance and employment costs. Both methods collect duckweed on a relatively large scale and, especially the Proskim water skimmer, can be used in many different water bodies and gradients. Additionally, size or other vegetation is no limitations for these methods. However, the suitability of a collection method depends for a large part on the specifics of a water body, such as size, shape, water quality and vegetation. Therefore, in order to decide which method to use the specific characteristics of each water body needs to be evaluated.

Before determining the end use of duckweed (see the flow-chart figure 5.4) it is necessary to analyze the level of contamination. Duckweed takes up nutrients and contaminants from the water, and therefore a primary benefit of this plant is public water purification. As urban water bodies and duckweed are almost always contaminated the potential use for food or animal feed is currently slim. According to current legislation duckweed used for food or animal feed needs to meet strict standards and duckweed collected from urban water bodies does not meet these standards. According to the researchers, the most useful product of urban grown duckweed is bio-energy, especially when duckweed is highly contaminated. Wet duckweed can be used with hydrothermal processing, which has the advantage that less time and costs are needed to dry the duckweed. By hydrothermal processing bio-oil and biogas could be produced. The use of duckweed in biogas installations is already taking place and biogas companies show great interest in the potential use of

duckweed in their installations. Finally, for mildly contaminated duckweed, the most suitable usage of duckweed will probably be natural fertilizer. These type of products can help meet the demand for fertilizers and have a higher content of phosphorous and nitrogen than commonly used fertilizers.

Samenvatting

Dit verslag bespreekt de potentiele mogelijkheden met betrekking tot het gebruik van eendenkroos wat zich bevindt in water in stedelijk gebied. Dit onderzoek is uitgevoerd door zeven masterstudenten van de Universiteit Utrecht in opdracht van KWR wateronderzoeksinstituut en Hoogheemraadschap Delfland. Het onderzoek bestaat voornamelijk uit literatuur onderzoek, aangevuld door interviews met experts. Intensieve kroosbedekking in water in stedelijk gebied veroorzaakt problemen aangaande stank, uitzicht en de ecologische waterkwaliteit. Omwonenden klagen vanwege de stankoverlast bij de gemeente of waterschap; de Nederlandse overheid is verantwoordelijk voor een goede ecologische waterkwaliteit. Om deze redenen zullen er oplossingen aangedragen moeten worden hoe het beste om te gaan met eendenkroos groei. De ideale oplossing zou zijn om het kroos om te vormen van afvalproduct naar economisch waardevol product en om dit vervolgens op de markt te brengen.

Er zijn twee basale manieren om met het kroosprobleem om te gaan: preventie en collectie. Of het geschikter is om kroosgroei te voorkomen of om het gegroeide kroos te verwijderen hangt af van het specifieke oppervlaktewaterlichaam, kwaliteit van het kroos en behoefte van de lokale autoriteiten. Om eendenkroosgroei te voorkomen kunnen verschillende manieren van aanpak worden overwogen. De meest effectieve preventiemethode is het verlagen van de nutriëntenconcentratie in het water. Dit kan bewerkstelligd worden door middel van het baggeren van nutriëntrijke sedimentlagen. Echter, initiële kosten voor baggeren zijn hoog en om nutriëntreductie een duurzame en structurele oplossing te laten zijn dient de toevoer van nutriënten in het water verminderd te worden. Nutriëntreductie dient een breder maatschappelijk doel dan de preventie van kroos alleen, namelijk de verbetering van algehele ecologische (water)kwaliteit. Kosten voor nutriëntreductie zullen dus niet alleen toegeschreven moeten worden aan de preventie van eendenkroos. Een tweede interessante preventie mogelijkheid is het lokaal versnellen van de stroomsnelheid. Dit laat het kroos wegspoelen en voorkomt kroosgroei. Dit kan door middel van pompen of het creëren van een stuwtje. Het is erg afhankelijk van lokale omstandigheden of deze toepassing mogelijk is, maar in sommige gevallen kan dit goedkoper zijn dan baggeren en nutriëntenreductie.

De meest geschikte collectiemethoden zijn het plaatsen van kroosschermen en overige handmatige methoden vanwege de hoge efficiëntie en relatief lage initiële kosten. Anderzijds zal op de lange termijn handmatige collectie waarschijnlijk hogere kosten hebben dan, bijvoorbeeld, de Proskim water skimmer en de 'Duckweed Guzzler'. Deze laatste twee zijn methoden met relatief hoge initiële kosten, maar hebben daarentegen lage onderhouds- en arbeidskosten. Beide methoden zijn in staat kroos op een grote schaal te verzamelen. De Proskim is bijzonder geschikt in verscheidene waterpartijen en gradiënten. Bovendien vormen schaalvergroting en overige aanwezige vegetatie geen belemmering voor deze methode. Welke collectiemethode het meest geschikt is voor de verzameling van eendenkroos hangt sterk af van karakteristieken van het waterlichaam zoals grootte, vorm, water kwaliteit en overige aanwezige vegetatie. Een heldere afweging van deze karakteristieken is nodig om de uiteindelijke meest geschikte collectiemethode te bepalen.

Voordat bepaald kan worden wat de beste toepassing is van het verzamelde kroos (zie flow-chart in figuur 5.4) is het belangrijk dat het gehalte van de vervuiling wordt bepaald. Eendenkroos neemt nutriënten en vervuilende stoffen op in het water waardoor het water gezuiverd wordt, een eerste positief effect van eendenkroos. Omdat water in stedelijk gebied bijna altijd vervuild is, is het ongeschikt voor gebruik in dierlijke of menselijke voeding. Huidige wetgeving schrijft strenge eisen voor aan voedingsproducten waar eendenkroos uit stedelijk oppervlaktewater niet aan voldoet. Dit

onderzoek wijst uit dat de meest geschikte toepassing voor eendenkroos uit stedelijk gebied bio-energie is, ook wanneer het kroos zwaar vervuild is. Nat kroos kan hydrothermaal verwerkt worden met als voordeel dat het droogproces minder tijd kost. Bij dit proces kan er bio-olie en biogas uit het kroos gewonnen worden. Het gebruik van eendenkroos in biogasinstallaties vindt al plaats in Nederland en bedrijven laten grote interesse zien naar het potentiële gebruik van kroos in hun installaties. Tenslotte kan enigszins vervuild kroos geschikte worden gemaakt voor het gebruik als natuurlijke meststof. Dit product kan voorzien in de vraag naar meststoffen en heeft over het algemeen een hoger nitraat- en stikstofgehalte dan de meeste meststoffen.

Contents

List of figures and tables

List of figures

List of tables

Introduction

The Netherlands is known all over the world for its beautiful water bodies. This characteristic landscape is unique to this country, particularly, in urban areas where cities spaces are alternated by buildings, roads and canals. The presence of many waterways entails the existence of many different plants that reside within these basins. Over the years, a certain aquatic plant, commonly known as duckweed, has attracted the interest of the research community and water management authorities due to its potential as water purifier tool and products compound (Iqbal, 1999, p.11; Leng, 1999).

Duckweed is scientifically known as the taxonomical family of *Lemnaceae*. It is the smallest flowering plant that free-floats on the surface of still or slow moving bodies of fresh water. It lives in nutrient-rich environments, grows exponentially in size, and has the potential to completely cover the surface of a water body in less than 24 hours (Verma & Suthar, 2015, p.3). One of the particularities of duckweed is its ability to absorb nutrients, heavy metals, phenols, pesticides, dioxins, and pathogens from the water and it is often used as a remediation mechanism for basins with poor water quality (Leng, 1999; van der Spiegel et al., 2013, p.667). Moreover, duckweed is considered to have a high ductility and can be used in the manufacturing of many products because of its high protein and starch content (Verma & Suthar, 2015, p.3). Particularly, in the past years businesses have increasingly developed an interest towards this plant, specifically in regards to bio-energy production (Verma & Suthar, 2015, p.3). On the other hand, if uncollected, duckweed blocks sunlight from passing through the water, resulting in a reduction of aquatic life (Leng, 1999; van der Spiegel et al., 2013, p.667). Furthermore, citizens, especially in cities in the Northern and Western part of the Netherlands, have raised complaints to the water authorities and municipalities concerning the unpleasant odor caused by duckweed. Currently Delfland Water Authority (DWA) removes duckweed only when complaints are raised and processes it as waste. Because most of DWA's income comes from cities, this organization wants to increase its visibility and return part of its tax revenue by providing visible community services. Considering the many possibilities of duckweed processing, the drawbacks that arise from not removing it from the waterways, DWA is interested in knowing whether there are possibilities to turn duckweed "from trash into treasure".

Given the time at hand, this research covers only partially the goals set by the client and aims to answer the research question:

In what way can prevention, collection, and processing methods of duckweed in the urban water systems of The Netherlands be managed to foster a transition from undesired waste to a useful sustainable product?

The above research question will be addressed by integrating the results derived from answering these disciplinary sub-questions:

1. What kinds of duckweed species are known to exist in the urban water systems of the Netherlands and what are their characteristics?
2. What are the (possible) prevention methods used to solve duckweed related problems in urban water systems?
3. What are current and potential duckweed collection and transportation possibilities?
4. What products can be derived from duckweed?
5. How can the niche market of duckweed transition into the mainstream market?

An overview of the steps taken during the research is shown in the flow diagram below (Figure 1.). Because the topic deals with aspects from various different scientific disciplines, this study is conducted in a transdisciplinary manner where the research team cooperates across disciplinary boundaries.

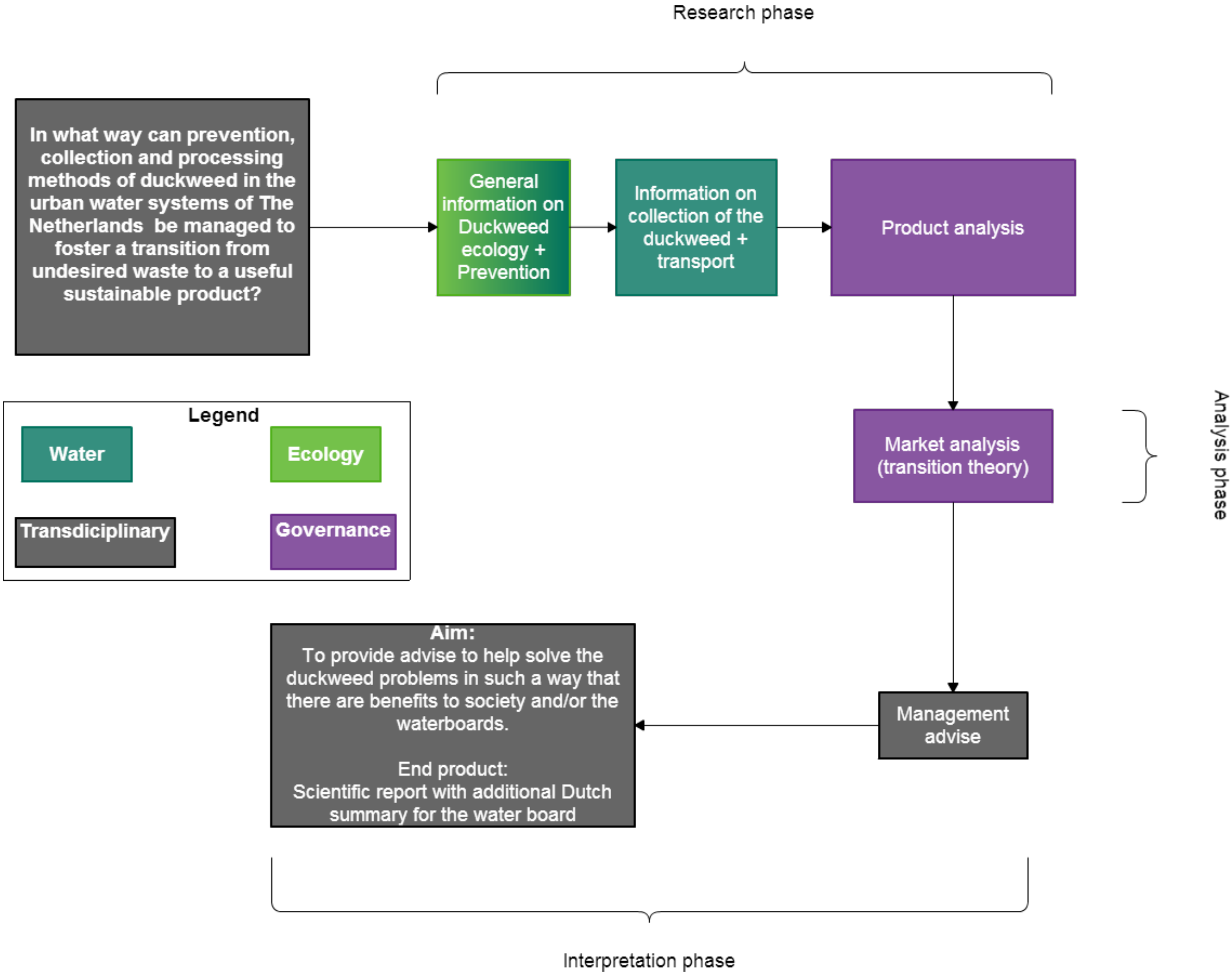

Figure 1. Flowchart duckweed research

The different subjects were researched by the students of the specific discipline involved, as indicated in the research phase of figure 1. During the research phase, students from the other disciplines commented on the research in order to integrate other viewpoints and ideas into the disciplinary parts. When these disciplinary parts were completed, they were integrated in the Market Analysis (chapter 6) using the transition theory as explained in chapter 1. That way, the results of the disciplinary researches were combined using one theory. The outcome of the analysis was in turn used to write a combined management advice. This management advice consists, among others, of the potential steps that the clients should take when considering utilizing duckweed. The client requested no additional product outcomes than what can be found in this document. Chapter 1 (transdisciplinary) describes the methodology and theoretical background used for the report. The goal set for this research will be achieved by first analysing the ecology of duckweed in Chapter 2 (ecology). Secondly, current and potential prevention techniques are evaluated in Chapter 3 (ecology/water management). Thirdly, Chapter 4 (water management) describes possible collection and transportation methods. Afterwards, the potential of duckweed as product compound are identified in Chapter 5 (governance) while chapter 6 (governance/transdisciplinary) assesses branches of the Dutch market where these products might be placed. Finally, in Chapter 7 (transdisciplinary) some management advices and indications on how to steer the use of duckweed towards useful sustainable products will be given.

Client affiliation

This research is commissioned by KWR Watercycle Research Institute, ORG-ID and Delfland Water Authority. The first organisation works towards the goal of providing assistance that will successfully help society manage their waters, using three different methods. First, KWR is involved in creating new knowledge in regards to healthy, sustainable, innovative and efficient tools that will help administer waters. Secondly, they work as a bridge between civil society, researchers, businesses and policymakers. In doing so, KWR supports its final goal which consist in creating a forum where stakeholders can interact and design business-like and cost-efficient practical solutions to everyday water issues, keeping in mind the impact of such solutions on the wider hydrological system. Therefore, KWR encourages and supports development of societal innovations in and around water management (“KWR Watercycle Research Institute,” NN).

DWA is the responsible body for dealing with management of waterways within the area comprised between Delft, Midden-Delfland and The Hague, located in the South-Holland province. The board of this authority, not unlike municipalities, is directly elected and composed by representatives of stakeholders relevant in the area (citizens, industry, owners of open land, mainly farmers, and owners of natural resources). DWA has three main mandates: maintaining dams and dikes, assess water quality, and control water levels. These functionalities are financed with taxes paid by residents and businesses of the area DWA manages (“Delfland Water Authority — Hoogheemraadschap van Delfland” NN).

ORG-ID is a management and policy consulting firm, mostly active in the area of the physical environment. The firm taps into broad knowledge and extensive experience in working in the public sector. In ORG-ID’s view, policy making is a continuous process that involves many parties and interests. Cooperation between different stakeholders leads to better results, not only in the near future but also in the long run. With this perspective, ORG-ID works on strategic cooperation, program management and organization development.

1. Methodology

1.1 General data collection

The research methods used in this research consist mainly of literature review complemented with expert interviews. For the first part of the report a division is made between different relevant subjects: the ecology of duckweed, its prevention, collection and transport, and a product analysis. For each subject a literature research using scientific databases is done after which articles were selected based on relevance and number of citations as this usually indicates quality, as well as the abstracts accompanying the articles. Using the snowball technique duckweed experts were selected for interviews (Bernard, 2011). The setup of the interviews were semi-open with a subject list (Ibid.). The results of the interviews and literature review were combined to overviews of the ecology, prevention, collection and transportation of duckweed and the possible products derived from duckweed. Because the methodology is explained in this chapter, the following chapters will not deal with methods extensively.

1.2 Theoretical framework: Transition Theory

As duckweed is a product with high potential but is not yet integrated in the mainstream market, transition theory could be useful for analyzing the current barriers and possibilities of duckweed processes vis-à-vis other products and processes, as well as to analyze what possible pathways for duckweed might entail. In other words, duckweed products are not entering an empty market, but an already existing market full of other competing products. Further, this approach was introduced officially with the fourth Dutch National Environmental Policy Plan as a governmental policy-making pathway (Loorbach & Rotmans, 2010, p.238). It is believed that this perspective will enable innovation within the policy arena through the introduction of an experimental attitude lead by general societal gains rather than strict goals (ibid.).

According to Rotmans et al., "[a] transition can be defined as a gradual, continuous process of change where the structural character of a society (or a complex subsystem of society) transforms" and often takes a number of decades to be completed (Rotmans et al., 2001, p.16). In this case, the sub-system consists of water quality and sustainable products that provide a positive contribution to society. Transition theory assumes that every transition in society is a coevolution in which different subsystems shape, and reshape, each other (Rotmans et al., 2001, p.16; Kemp et al., 2007, p.78). It is especially important to look at coevolution in regard to governance since it shows that there are cause-and-effect loops over different scales and between different systems (Ibid., p.79).

Any transition can be characterized and analyzed by looking at the various levels of transition size and speed (Rotmans et al., 2001, p.19). First, there is the *niche* or *micro* level, where individual actors are involved in the transition processes, but have no impact on the status quo because they are too small and few in numbers to be influential. In this research the duckweed as a source of new products. Secondly, the *regime* or *meso* level is the level of the status quo's organizations, practices, ideas, and interaction between clusters of actors and large organizations. Hence, the current market which duckweed wishes to compete with. Thirdly, the *landscape* or *macro* level identifies the entire set of interacting actors, networks, organizations and governments that operate in a context of, among others, rules, regulations, ideology, culture, paradigms, and economic situations (Rotmans et al., 2001, p.19). The landscape thus shapes the status quo and the possibilities of duckweed transitioning into the market. The *regime* can try to improve its current practices when confronted with an emerging *niche*, or can try to use other means at its disposal to prevent the *niche* from growing (Rotmans et al., 2001, p.19). If the *niche* can resist these counter pressures, it can eventually overcome the *regime,* and become one itself. The *micro* level actors can be supported by actors from the *meso* and *macro* levels by providing the circumstances for the *micro* level actor to be effective, as long as the *micro* level actor is able to construct an enduring design that withstands the pressures of the *regime* (Rotmans et al., 2001, p.20). The interaction between the levels above described can be summarized by the figure 1.1.

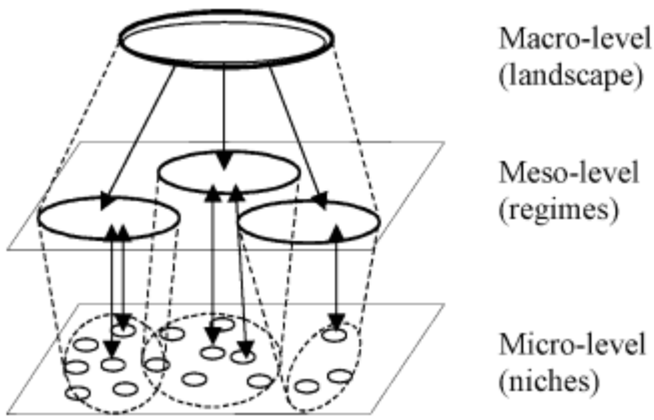

Figure 1.1 Multi-level interaction

A *regime* operates in a, for itself, logical manner. Regimes can be characterized by having an entire set of rules, principles, infrastructure, institutions, knowledge-base, scientific understanding, experiences, practices, and ideas that push the operations within that regime in a certain direction (Kemp et al., 1998, p.182). In other words a paradigm. To diverge from this set of criteria is difficult, and it is even more difficult to change them. If a *regime* is based on technology, it is called a *technological regime* (Kemp et al., 1998, p.182). These regimes are even stronger because they affect the world outside of the *regime* as well. They affect and co-produce social behavior, norms and values, and expectations. Through this, additional social barriers are created for niches to emerge.

A transition moves through four transition phases (Rotmans et al, 2001, p.17). First, a *pre-development* phase, where the status quo in a system is maintained, but, where on a *micro* level, the foundations for a large transition are created. Second, a *take-off* phase, where the status quo processes need to make space for the newcomers. Third, an *acceleration* phase, where the transition is in full swing and continues to gain momentum by support and benefits from other actors and areas through so-called positive feedback loops. If, for example, a transition occurs in the realm of electricity storage, that has a positive effect on the use of solar panels. Lastly, a *stabilization* phase, where the transition is completed and a new status quo is created (Rotmans et al., 2001, p.17) (Figure 1.2). Duckweed is still in the pre-development phase. No large-scale applications on the mainstream market have been found. However, as is explained in chapter 5, research and small-scale experiments are being conducted regarding the usage of duckweed.

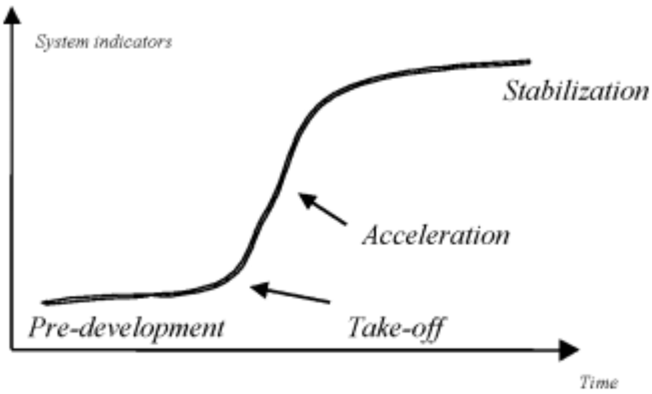

Figure 1.2. Transition phases (van der Brugge, 2005, p.166)

Transition theory encompasses historical, social and technical analysis through the assessment of the relation of three above explained levels, i.e. landscapes, regimes and niches (Foxon et al., 2010, p.1204). Research has focused on three main lines of analysis. Transition theory has first been used to evaluate historical events and dynamics that have fostered the transition (ibid). A second position taken by scholars consist in a more practical approach. This consists in developing a governance process that aids to foster a transition through interactive and recurrent interaction between stakeholders. This is called 'transition management' (ibid). Finally, the third approach aims at describing possible 'socio-technical scenarios' that analyze how various technological options in combination with strategies, policies and stakeholders' behaviors may concur to aid transition (ibid). The research will focus on the last perspective as explained in section 2.2. The approach will allow this research to integrate technological and social science and develop transition pathways based on a richer analytical ground (ibid, p.1211).

2.2 Transition pathways

In order to describe possible transition pathways of duckweed from niche to mainstream market, it is necessary, according to Foxon et al., to undertake three steps (2010, p.1205). First of all, investigating the existing *regime* and its main characteristics, processes and dynamics that may lead to change or stability (Foxon et al., 2010, p.1205). Hence, this research project understands the regime as the status quo: the mainstream market in which duckweed is considered a waste product. Furthermore, the main actors per product type, their positions, and currently used technologies must be identified. A regime does not function in isolation. External pressure, as public awareness, economic pressure, or international targets, and internal factors, organizational developments, institutional structures or markets, may play a role in decision-making e.g. the *niche* and landscape (Ibid.). Figure 1.3 below describes this stage by providing an example of the UK energy market.

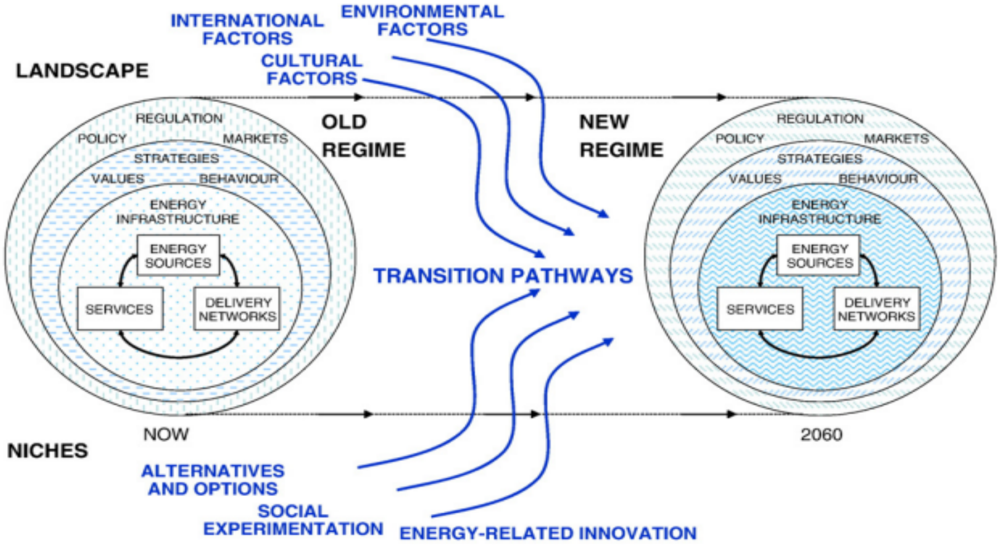

Figure 1.3. Transition pathways and possible influencing factors (Foxon et al., 2010, p.1206)

Secondly, it is important to analyze the *niche,* which in this research is the possibility of useful usage of duckweed*,* in detail (Foxon et al., 2010, p.1206). It is helpful to look at the various processes that occur within the *niche* and how the behavior and development of the *niche* might influence the overall stability of the system (Ibid.). Hence, the question arises whether duckweed has the potential to change the regime. The dynamics of a *niche* are influenced by many different systems and different obstacles are to be taken into account. When considering for example the success of urban farming, this is influenced by many factors such as urban planning, government regulations, weather conditions, media outlet, and popular culture. Thus when analyzing the potential of duckweed it makes sense to take many factors into account as well*.* In the case of a new technological system, the innovation dynamics play an important role in the development of the *niche* (Ibid.). The way the technological system is organized, what is allowed and what is forbidden in terms of innovation, determines partly, logically, how the *niche* actors behave. The technical aspects of both the regime and niche are taken into consideration (Ibid.).

Thirdly, it is necessary to analyze how *landscape* or *niche* dynamics can destabilize and change a *regime* (Foxon et al. 2010, p.1207). There seems to be quite some disagreement in the literature on the reasons and analyzing characterizations of *regime* change (Ibid.). The claims differ from looking at the direction of change (inside or outside of the *regime)* and whether or not the change was orchestrated or random, to the occurrence of external/internal shocks that suddenly open a *regime* to outsiders or demands change, or change that occurs through slow internal processes (Ibid., p.1207-1208). Foxon et al. propose to look at the governance styles of the system and its actors instead, in order to see how changes in governance practices can change systems (Ibid., p.1208). Therefore, in this research the landscape will focus on the overarching governance mode, the general social norms and legislation regarding the possible duckweed products and collection methods.

In order to perform the actual analysis, this research will follow in the steps of Foxon et al. (2010). The first step of the analysis is to analyze the *landscape*. The second step is to identify the characteristics of the *regime* in regards to duckweed. For example, that currently other resources than duckweed are used for animal feed, energy, fertilizer, soil enhancer and the other products discussed in chapter 5, as well as its other main characteristics. Thirdly, it is necessary to identify the characteristics of the *niche*, hence the duckweed as ingredients for the products discussed in chapter 5. Taken the aspects of step 1 and 2 into account, is there a possibility for duckweed products to move into the main market, or, how might duckweed develop and what influence would this have on the regime, are questions that need answers These three steps together will form the market analysis.

2. Ecology

It is imperative to understand how and where duckweed grows in order to assess the potential of sustainable duckweed collection and application. Therefore in this chapter sub question 1 will be answered: '*What kinds of duckweed species are known to exist in the urban water systems of the Netherlands and what are their characteristics?*'

Duckweed belongs to the botanical family of *Lemnaceae*, they are divided into four genera *Lemna, Spirodela, Wolffia*, and *Wolffiella* of which, to date, more than 40 species have been identified (Journey et al., 1994). Duckweed species are the smallest flowering plants, with most being sized below one centimetre and not exceeding three (Maessen, 2014). Their structure has been simplified by natural selection to the basics features necessary for survival, since the plant lacks leafs and stem (Journey et al., 1994; Leng et al., 1995). Duckweed, indeed, is characterized by an ovoid frond, which floats on the surface of water basins, and one or more roots (figure 2) (Journey et al., 1994; Leng et al., 1995). The roots have multiple functions, i.e. to collect nutrients and to stabilize the plant. As the species floats on water they are completely dependent on the available nutrients in the basins (Journey et al., 1994; Leng et al., 1995). Duckweed species are able to grow in temperatures between 6 and 33 degrees Celsius, but they are sensitive to frost, although, often survive by changing to an inactive state, called turion, sinking to the soil and laying there during the winter (Roovers, 2005, p.7-9). There five indigenous Duckweed species in The Netherlands (i.e. *Lemna minor, Lemna gibba, Lemna trisulca, Spryrodela polyrhiza* and *Wolffia arrhiza*) and others have been introduced over the years (i.e. *Lemna minuta, Wolffia columbiana* and *Azolla filiculoides*) (ibid). Recently invasive species have been brought to The Netherlands, but the impacts of such practices remain unclear (ibid).

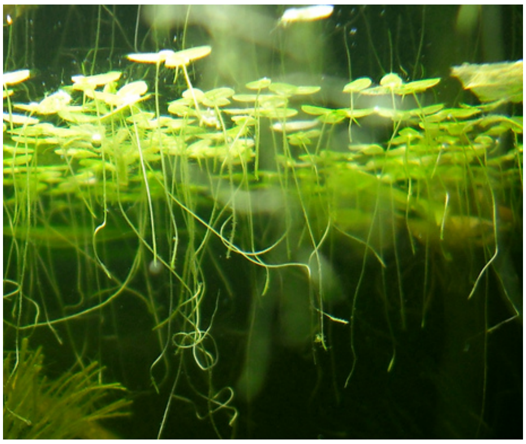

Figure 2. Floating duckweed (www. aquaterralive.com)

2.1 Environmental conditions & Distribution

The natural habitat of duckweed consists of fresh or brackish waters. They often do not survive in fast moving water (<0.3 m/sec) and are, therefore, common in sheltered lagoons (Leng *et al*., 1995). Moreover, duckweed can often be found in still waters with a depth between one and two meters and an organic rich soil (Roovers, 2005, p.8). Further, as above mentioned, duckweed livability depends on water contents, and therefore the presence of this plant is an indicator of nutrient rich waterways (Maessen, 2014, p.2). It appeared that Duckweed species favor ammonium more than nitrate as a nitrogen source (Roovers, 2005, p.9). Finally, the pH value of waters where Duckweed is commonly found varies between five and nine (Leng et al., 1995; Roovers, 2005, p.8). The characteristics of several duckweed species common in The Netherlands are shown in table 2.1. Duckweed is generally found in every province of The Netherlands, although, it is especially common in the province of South Holland, but not widely spread in Zeeland and Limburg (Maessen, 2014, p.8).

Table 2.1. Characteristics of individual duckweed species

Species	Environmental conditions	Characteristics	Distribution by province
Wolffia arrhiza	Shallow, fresh and nutrient rich waters	Sensitive to frost; not resistant against a brackish and salt environment	Almost only common in South Holland
Lemna gibba	Nitrogen and nutrient rich waters; capable to grow in full sunlight; possesses air cabins to float higher than other duckweed species	Forms turions during winter	Especially common in South & and North Holland and in peat areas in Utrecht
Lemna minor	Found in the water column; grows in the shade; diverse water qualities, can also grow in very small waters such a car trails in the mud	Resistant to frost	Especially common in South & and North Holland and in peat areas in Utrecht but also common in the rest of The Netherlands
Lemna trisulca	Found in the water column; extreme nutrient rich environment; also in brackish and fresh waters; can grow in shade and in sunlight	Unlimited growth in nutrient rich waters; less resistant to water pollution and troubled water	Especially common in South & and North Holland also found in the rest of The Netherlands such as Overijssel and Friesland
Spirodela polyrhiza	Less common, does not indicate nutrient rich environment	Form turions during winter	Especially common in South Holland and in lesser extend in North Holland and Friesland
Lemna minuta	Nutrient rich; still waters with a depth of a meter; organic rich soil; shadow tolerant	Invasive species in The Netherlands; remains green during winter	Especially common in South Holland

2.2 Composition & Contamination

Duckweed species mostly consist of water. A research in the United States on dried *Lemna Gibba* showed that further elements that can be found within this plant consist of crude protein, crude fiber, fat and ash (Hillman & Culley, 1978). However, the potential of the various duckweed species is vast. In table 2.2 potential duckweed composition is compared with three other crops. As shown by this comparison, duckweed species have an average of 37.0% of crude protein. This is higher than cottonseed and peanuts. Note that all of these crops are grown under human induced conditions and therefore the numbers are not applicable to natural circumstances. As duckweed has the capability to take up nutrients and micro contaminants such as metals and dioxins the contamination level of duckweed is dependent on the water quality it grows in. The water board Noorderzijlvest for example concluded that the investigated duckweed only exceeded dangerous mercury levels but was otherwise fine (Hoving & Holshof, 2012, p.25-26). A pilot study by Holshof et al. in 2007 had other results. The duckweed they investigated consisted of dangerous levels of dioxins and arsine (Hoving & Holshof, 2012, p.25-26). The difference in outcome is probably the cause of the different water qualities the samples were taken from.

Table 2.2. Potential duckweed composition compared to other crops (Hillman & Culley, 1978)

	Annual tons/acre (%)	**Crude protein (%)**	**Fat (%)**	**Fiber (%)**	**Ash (%)**	**Relative protein production per acre/year**
Duckweed(dry)	7.85	37.0	5.0	7.5	11.0	100.0
Soybeans (dry seed)	0.71	41.7	19.2	5.8	5.4	10.2
Cottonseed (dry)	0.34	24.9	24.7	18.2	3.8	2.9
Peanuts with skin and hulls (sun cured)	0.70-1.39	23.6	37.9	21.1	3.2	5.7-11.3

2.3 Eutrophication

Eutrophication is caused by the oversupply of nutrients in an ecosystem. During this process, runoffs from agricultural land, sewage systems and not to forget feces from ducks in the water and dogs near the water enter water basins (Roover, 2005, p.1). Nutrients from these leakages, such as nitrogen and phosphate, have a positive effect on the growth rate of water plants. Thus, eutrophication may cause waterways to get completely covered by duckweed. When this happens sunlight is blocked from reaching deeper waters, provoking a shortage of oxygen and consequently lowering photosynthesis rate of underwater plants and reducing the achievement of nutrient rich organic soil(hypoxia) (Maessen, 2014, p.2). This in turn has a positive effect on duckweed growth ensuring a positive feedback loop. Eutrophication can therefore lead to massive destruction of underwater ecosystems as many species do not tolerate such environmental conditions (Anderson et al., 2002).

Concluding, duckweed is a fast growing aquatic plant common in nutrient rich still waters. They are known to have adverse impact on water quality as a result of eutrophication. Removal or prevention of duckweed is, therefore, needed to counteract these negative effects. Due to its characteristics and composition, duckweed has the potential to be utilized and transformed into different products.

3. Prevention of Duckweed

As mentioned above, duckweed prefers certain environmental characteristics for optimal growth. One of the possible solutions to reduce the negative effects of duckweed and, at the same time, avoid duckweed collection costs is to alter the aquatic environment to prevent or reduce growth. In order to be implemented, these changes need to be economically feasible and not significantly damage the ecological situation. This section provides an overview of a number of strategies that can be used in order to prevent or reduce duckweed growth and will provide an answer to sub-question 2: '*What are the (possible) prevention methods used to solve duckweed related problems in urban water systems?'* In table 3.1 the major findings will be summarized.

3.1 Nutrients reduction

Under normal concentrations, all nutrients are used by the larger floating vegetation and plants attached to the bottom and no nutrients are left for the duckweed and consequently no duckweed will grow (Roovers, 2005, p.8). When nutrient concentrations increase due to eutrophication, the amount of nutrients in the water is no longer a limiting growth factor. Thus, the more nutrient rich the water is, the more duckweed will grow (Otte & van Hoorn, 2014, p.5). A way to limit the amount of duckweed growth is to reduce the nutrient level of the water. Nutrient removal is considered to be one of the most effective methods since duckweed species are unable to store any nutrients, thus, making them highly dependent on water contents (Hoving et al, 2012, p.18; Maessen, 2014, p.16). Further, this practice will immediately effect duckweed growth without significantly damaging the rest of the ecosystem (Hoving et al, 2012, p.18).

Reducing nutrients is a difficult process and it is practically impossible to directly remove them from the water. Particularly, the nitrogen: phosphate ratio is of relevance. Phosphate is often considered to be the main factor that hinders duckweed growth, thus, reducing the amount of phosphates can be sufficient to limit duckweed growth (Hoving et al, 2012, p.18). When nutrient concentrations are brought below threshold, it is important to keep them stable. In The Netherlands the major nutrient sources within urban environments are agricultural inputs from rural areas, sewage overflows, and duck feed leftovers (Roovers, 2005, p.33).

Furthermore, reducing nutrients in surface waters might also lead to the overall improvement of the ecological situation of basins in The Netherlands as well as aid meeting the goals of the European Nitrogen Directive (EU, 1991). When considering nutrient reduction as a possible prevention method, therefore, the assessment should also take into account further positive impacts that may rise from such intervention.

3.2 Overshadowing

Duckweed requires sunlight to grow and will hardly, survive in the shadow. One could, therefore, argue that overshadowing the water might reduce the growth of duckweed (Roovers, 2005, p.26). Overshadowing could be done by placing platforms over the water. However, this technique is hard to implement, not aesthetically pleasing and might negatively impact the growth of other species living in those waters. Planting trees on the water banks is an overshadowing alternative that might reduce above mentioned drawbacks. However, nutrients provided by falling leaves might cause an increase in the duckweed growth in comparison to the original situation. Despite the shadowing effect, trees are more likely to be a cause of duckweed growth than a prevention method (Maessen, 2014, p.3).

In some waters, due to small currents or wind, duckweed tends to concentrate near bends, bridges, in dead ends or in front of an underwater culvert (Roovers, 2005, p.26). A second, more practical, option consists of overshadowing only the locations where duckweed is concentrated. This method of selectively overshadowing makes this prevention procedure a feasible option.

3.3 Dredging

By deepening waterways duckweed growth can be reduced (Roovers, 2005, p.26). This must be done carefully when dredging the upper sediment layer because these activities can induce nutrients seepage from the soil (Maessen, 2014, p.12). This can increase nutrient concentration in the water and subsequently lead to an increased growth in duckweed. It is observed that the appearance of a duckweed cover after dredging is often temporary because water quality structurally improves after dredging (Maessen, 2014, p.12). However, in some cases duckweed concentration increases with respect to other water plants after dredging. This is probably related to the fact that dredging removes most of the water plants attached to the bottom while a lot of small floating duckweed stay behind (Roovers, 2005, p.26).

Secondly, by removing the top layer of the soil, nutrient concentration in the water might also be reduced (Roovers, 2005, p.26). This might in turn lead to decrease duckweed growth, further discussed below. Research has shown that dredging activities in peaty areas have the best effect on reducing duckweed concentration (Maessen, 2014, p.3).

Thirdly, dredging removes the duckweed seeds (turions) from the bottom of the waterway. When sediment removal occurs in late summer or fall, seeds which were supposed to hibernate will be removed as well and hence lead to less duckweed in subsequent spring (Roovers, 2005, p.3).

3.3 Flushing

More flushing of the water system can reduce the growth of duckweed (Roovers, 2005). A first option to be considered requires increasing fresh water run through the system in order to raise flow velocity. Secondly, when basins can be artificially managed and it is possible to control seasonal water levels, water levels can be reduced during a (freezing) period. Indeed, most duckweed turions cannot withstand freezing temperatures. Therefore, reducing water levels and allowing turions to freeze, can bring duckweed growth almost to zero (Roovers, 2005, p26). Finally, other water management practices to reduce the amount of duckweed is to heighten culverts above the water level or to create a small overflow so duckweed can go with the water flow (Maessen, 2014, p.33).
Since most surface water levels in The Netherlands are artificially managed, increasing flow velocity and reduce seasonal water levels might be possible in some cases. Feasibility of such practices within city waters will depend on characteristics of waterways. However, when duckweed is already present care must be taken that this plant is not flushed to another stagnant water bodies.

The best suggested prevention method would be to reduce the amount of nutrients in the water. Initial nutrient reduction can be achieved by dredging the nutrient rich sediment on the bottom. A second advantage of the dredging is that duckweed turions in the sediment will be removed as well, which reduces new duckweed growth in the coming season. However, in order to let the nutrient reduction be successful, the input of nutrients need to be reduced as well. Reducing nutrient input is difficult and expensive to achieve as many stakeholders are involved. Nutrient reduction does not only serve the goal of duckweed reduction, but aims at a better ecological water quality which serves a broad societal interest. A second feasible prevention option would be to locally increase flow velocity. This could be done by extra water pumping or the installation of overflows. However, feasibility strongly depends on the facilities present and characteristics of the water body.

Table 3.1 Summary of duckweed prevention methods.

Method	**Process**	**Applicability / feasibility**	**Notes**
Reduction of nutrients	- Duckweed is very dependent on nutrient concentration in water. By reducing nutrient content duckweed will die or unable to grow.	- Effective and implementable in all waters. - Difficult to directly extract nutrients. - Indirect extraction by dredging or duckweed removal - Prevention of (anthropogenic) nutrient input	- Sometimes requires expensive measures. - Can be integrated with ecological improvement of surface water (e.g. Nitrogen directive). - Only removal is not sufficient, nutrient input needs to be lowered systematically.
Deepening / dredging	- Duckweed does not grow in water deeper than 1.5m. - Removal of nutrient rich sediments (see nutrient removal). - Removal of seeds in late summer / fall so no duckweed will grow in subsequent spring.	- Practically almost all waterways in The Netherlands can be dredged. - Very suitable for peaty areas.	- Dredging is expensive. - Dredging causes nuisance for inhabitants. - When sediments are very nutrient rich, mixing can cause more duckweed to grow, although this is a temporal appearance.
Flushing	- Flushing away existing duckweed - Duckweed favours stagnant water and will not grow when flow velocity is too high.	- Only possible when water level is already artificially regulated. In these cases pumping rates will have to be increased. - Heightening culverts above water level so duckweed can flow away. - Adding overflows so locally flow velocity increases and duckweed flushes away.	- Depends on availability of fresh water. - Care must be taken flushed away duckweed will not concentrate in downstream parts. - Depends on characteristics such as to what extent pumps are present and dead ends.
Winter water level reduction	- If water level is low enough during cold periods, turions on bottom will freeze and die, leading to less duckweed in subsequent spring.	- Only possible when water level can be reduced to sufficient level.	
Overshado wing	- By blocking of sunlight the duckweed will die.	- Impractical to overshadow complete waterways. - If present, overshadowing of places where duckweed concentrates possible.	- Duckweed only dies; nutrients remain in water which can cause a new duckweed bloom when exposed to sunlight.

4. Collection and transport possibilities of duckweed

Duckweed is becoming a problem in urban areas mainly due to the unpleasant odour resulting from the degradation of perished plants, which can be prevented by regularly removing it. This chapter therefore focuses on different possible collection methods, performed by hand or machines. Sub-question 3 will be investigated in this chapter: '*What are current and potential duckweed collection and transportation possibilities?* '

It will address the main characteristics of each technique by highlighting the costs, time employed and collection efficiency in percentage which is the amount of collected duckweed compared with the total duckweed in a pond. A careful collection of duckweed ensures higher water quality and this practice could also have a beneficial impact on the basin by, for example, allowing the removal of waste out of the water combined with the removal of duckweed (Maessen, 2014). Further, this chapter will indicate possible innovations that could lead to technological advancements within collection methods.

Following the water authority of Vallei and Veluwe, the parameters duckweed coverage, reachability and morphology are of importance (Maessen, 2014). These parameters influence the time, costs and the choice of possible mechanisms to remove duckweed. Collection time is not easily determined and is dependent on the size, amount of duckweed present and obstacles impeding the access to the waterway. This element has, also, a direct impact on the expense necessary for the collection. Further, considering costs, literature estimates them in different units, i.e. per hour, per size of removal or initial costs of machineries. Due to this issue, comparison might be difficult. Therefore, in regards to time and costs an approximation has been made. Moreover, it is important to mention that when considering urban waterways, other factors need to be taken into account that might limit the options available for collection. Certain collection methods are dependent on water depth, e.g. using boats, and waterways surroundings, including vegetation on river banks, is an important determinant for the collection method to be used.

4.1 Known collecting methods in the Netherlands and internationally

According to Arthur Hagen, a consultant for the city of The Hague and the DWA, both the municipality and the water authority are extensively using different duckweed collection methods and working on improving these technologies (2015). Most collection methods that will be discussed below are currently being used in The Netherlands. However, the initial pump with culvert and the Proskim water skimmer have not yet been employed by either "Waterschap Delfland" or the municipality of The Hague, and are mostly used in the United States of America (USA). The selection of collection methods based on the pertinence of the techniques.

Duckweed screen

The company Berkhof BV collects duckweed from urban waters with the help of duckweed screens which consist of a net tied to a float. These nets are laid vertically in the water and the float is pulled toward a side of the basin so that the duckweed can be collected using landing nets. This approach is conducted by manpower and has a collection efficiency of 80% - 98% and is time consuming. This method is not feasible for water bodies which have an irregular shape and high presence of vegetation, because the large screen cannot reach irregular and vegetated places. The costs for this method are estimated around €200 per hour and can be considered lower in the short term since there is no necessity for an initial investment on machineries purchase (Maessen, 2014, p.25).

The crane method
Another method is used by a contractor named Harry Blokland, whereby a boat skims the duckweed from the water utilizing a crane with a filter at the bottom to remove the duckweed out of the water. This method is costly due the use of machineries, the collection efficiency is relatively low, 70% - 85%, but time is significantly reduced in contrast to manual collection. This method costs around €110 per hour, for boat, crane and labor. Additional costs of around €722 might be accounted for the delivery of equipment and transport of duckweed. (Maessen, 2014, p.26).

Krooskarper
The company Reijm BV uses a so called "Krooskarper". Since this method has recently been developed, costs might be unreliable and efficiency level are still unknown. The "Krooskarper" is a mowing boat used to trim aquatic plants which has been redesigned to in order to collect duckweed. This has been achieved by changing the saw into a V-shaped landing net. The duckweed is collected and stored within the net inside the boat. The boat is unfeasible for shallow waters due to the propeller behind the boat. This method is estimated to cost around €200 for one hour (Maessen, 2014, p.26-27).

Duckweed catamaran
A relatively inexpensive collection method is designed by the contractor called Ch. Portengen. This company designed the "Duckweed catamaran", where two floats are connected by a conveyor belt that collects duckweed using manpower. Although, this method is susceptible for shallow waters and extremely time consuming, it has a collection efficiency of 80% and it will cost approximately €125 for one hour (Maessen, 2014, p.27).

Duckweed wheel
A "duckweed wheel", created by Bom Aqua BV, has a similar design to the previously discussed method (duckweed catamaran), where a conveyor belt held by two floats is used to collect duckweed. However, this machine does not require labor and is powered by solar panels. This method is considered to be not very efficient in the collection of duckweed since it has low collection efficiency, excessive collection time and a high chance of having power shortages because of shadowy places and dirty solar panels (Maessen, 2014, p.28). The only costs of such method could consist in the initial investment accounted for €4 000 (Maessen, 2014, p.28).

Duckweed Guzzler
A recently designed method by the 'Waterschap Rijn en IJssel' is called a Duckweed Guzzler ('kroosslurper'). This method consists of a box and a pipe. The box creates or uses a present gradient of the water body and will accelerate the water flow in order to collect the duckweed into the box and transport it through the pipe to the bank. However, in some urban waters there is no gradient, and is therefore created by the Duckweed Guzzler. Another idea is that a pump could be used to bring in the water into the Duckweed Guzzler. The advantage of a duckweed Guzzler is its transportability. The Guzzler can easily be transported after collecting the duckweed. Moreover, the duckweed could be easily removed from the Guzzler via a conveyor belt (Raaphorst, 2015, p.10-15). This conveyor belt could transport the duckweed directly in a bag for further purposes. Other advantages of a Duckweed Guzzler are the relatively high speed of duckweed collection (a pond of about 1000 m2 is cleaned in 2 days). This method could be combined with solar energy. This collection method is conducted by Bom Aqua BV (Bom Aqua BV., NN) and will probably cost initially around €20.000,00, which is €5.000,00 for the Guzzler and €15.000,00 for the conveyor belt. However, these machines could be used for more places, so the costs for one-off collecting duckweed will be much lower (Bom Aqua BV., NN).

Initial pump with a pipe and a culvert
Tamra Fakhoorian, president of Green sun products, uses an initial pump with a pipe and a culvert to collect duckweed and transport it by trucks for further processing. This pump costs about around €2200 and harvests 800 pounds of duckweed in four minutes. However, this collection method can best be used in areas with an extensive duckweed growth, e.g. duckweed farms, because initial costs are too high vis-à-vis the projected benefits (Fakhoorian, 2015). Furthermore, there are uncertainties about the technical aspects of this design, the efficiency of the collection and the per hour costs, which Fakhoorian could not disclose.

Duckweed water skimmer
The American company Proskim designed a duckweed water skimmer which pumps the upper water layer from a small floating unit in the water to an onshore filtration unit (see figure 4.1). The floating unit creates a "vortex of water" that draws in the duckweed. The floating unit is connected by hoses to the onshore filtration unit. This unit separates the duckweed from the water. The water flows back to the water body while the collected duckweed stays on the shore (Proskim, 2013). According to their website this installation cost about €5 753. The machine collection time is considered extremely long, however, there is no manpower needed. Additionally, the unit is easily transported.

Fig. 4.1. A Proskim duckweed skimmer (Proskim, 2013).

Intensive manual duckweed harvesting
This collection method is considered pre-emptive, which entails that the first harvested amount of duckweed is lower than when collected at a later stage. However, the unpleasant odor should disappear after this method is applied (Riemer, 1994; Verma & Suthar, 2015). The collection is mostly conducted through the use of landing nets and a boat to reach the further ends of the waterways (Raaphorst, 2015, p.4-9). An advantage of this method is a lower waste content, as this could be separated before collection of duckweed. Since it is difficult to created machines which separates duckweed from waste, the pre-collection separation might result in a higher value of the collected duckweed (Hagen, 2015). Therefore the amount of duckweed remaining the ponds is

sufficient to maintain a high water quality and food for animals, while the bad odor caused by duckweed surplus is reduced.

The costs of intensive manual duckweed harvesting in the city of The Hague in a whole growing season from May until October will be about €15 876 (Raaphorst, 2015, p.4-9). These costs include labor, travel and collecting equipment for an area of 3 250 m^2 divided over three different ponds in the city. This collection results in 60% efficiency with 80% duckweed covering. This collection method is extremely time-consuming. Further, costs are high compared to other, more technological, methods. Yet, this method could be used in almost all urban water bodies without the need for large machinery and might be a mean to create employment. If this method is combined with public participation or, for example, unemployed citizens, costs would be extensively reduced.

4.2 Future innovations in collection methods

This section focusses on designs or ideas of collection of duckweed in urban waters developed by the researchers of this project. Some of the previously discussed prevention measurements could easily be combined with the collection of duckweed and thus lower the need of collection. In some cases the ponds should be adapted to create for example a gradient in the water pond or channel, such a gradient could easily be used to collect duckweed at a point. Duckweed collection could be combined with a culvert, however in this case the culvert should be located above the water surface for a part. Through this culvert the duckweed will be transported to another channel or pond. If the culvert contains a net it could capture the duckweed inside the culvert. In this case, the culvert should be adapted in such a way that the collection net could easily be removed when it is fully loaded with captured duckweed. The net is situated inside the culvert, so the only work for collecting the duckweed is emptying the net (Capelle aan den IJssel, NN). This method will have relatively low costs (low initial costs and little working time by employments) and the collection time will depend on the current in the channel or pond (will probably be several days).

Another collecting method could be designed from valves in urban canals. These canals already have such valves for preventing duckweed transportation to other canals. These valves ensures a proper transport of water by preventing vegetation or waste (at the surface) to migrate to the other canals. If these valves were combined with “big bags” as discussed in section 4.1 (Raaphorst et al., 2015), then duckweed could be collected. This collected duckweed will be of a low quality because it includes waste. However, this method could be easily created and applied in cities, hence reducing the amount of duckweed and the associated odor. The costs for this method will be relatively low, like the method with a culvert, also the collection time will probably be several days.

In almost all ponds and channels there is a flow, therefore the duckweed in often situated together caused by the flow. If it is possible to create a roof above this point with a lot of duckweed it would be a potential method to prevent duckweed or collect it after the duckweed dies. The roof will cause less sunlight, therefore the duckweed will die. If duckweed dies it will dry, therefore it is easier to collect and transport (weighs less). This method will be relatively cheap and the duckweed could be collected in a few hours (Nieuwenhuizen, 2010).

4.3 Transport (current and possibilities)

When duckweed is used for further processing or going to a waste dump, it needs to be transported. Transport costs, energy use GHG emissions and scale have to be considered. These issues will be assessed in the current and possible transport ways for transporting duckweed.

Duckweed is collected in the green state (wet duckweed). Transporting wet matter is costly as fresh duckweed consist of about 92-94% of water (Leng et al, 1995). Therefore the energy required to dry fresh duckweed is high and the dry matter will only consist of a small part of the original duckweed. The wetter duckweed is, the more energy is needed to dry it. Drying can be done by gas heating or pressing. In research done by Holshof et al. (2009) fresh duckweed was transported to a drying facility where in 30 hours duckweed was dried at 40 degrees Celsius to 90% dry matter (Holshof et al, 2009, p.11). They argue that drying will be too expensive to turn it into a competitive market product. Moreover, too much energy is needed for this process, therefore it is not sustainable. A better process, according to them, is pressing the water out of the duckweed (Holshof et al, 2009, p.11). This reduces the water content and consists of the simple step of pressing the wet matter. Other research indicates that pressing duckweed could reduce the water content with 50% (Nieuwenhuis & Maring, 2009, p.25). It might be an option to leave the collected wet biomass for some days on the collection site, in this way also a lot of water could be lost before transport (depending on the weather and site availabilities).

To design good transport options, one needs to have information about biomass quantities. This is not only useful for the design of transport, but also for product/processing possibilities. It is, unfortunately, difficult to know how much biomass actually is collected as it depends on the thickness of the duckweed layer in the water, the collection method and the surface area. For example considering the thickness of the biomass layer, it was found that when using cultivated ponds, there would be $500 g/m^2$ fresh duckweed biomass (Derksen & Zwart, 2010, p.12). But such an amount of fresh duckweed could not everywhere be harvested.

Research papers about transport costs (also in terms of energy and GHGs) of biomass were not found to be applicable to this project. For more complete modelling of the transport of biomass to a bio refinery, the IBSAL model is advised. This model can make a simulation of the way biomass goes from the field to a bio refinery. It estimates the cost, the greenhouse gas emissions and the energy input needed for collection and transport (Kumar & Sokhansanj, 2007).

4.4 Favorable methods for collecting and transport duckweed in urban areas

In Table 4.1 an overview of the different collection methods are given. They are assessed based on the following parameters; scale, water quality, costs, executing authority, transport, collection time and specials.

First, scale. This parameter refers to the size of the water body used for collection. The scale ranges from small, medium and large. unfortunately, exact sizes (in square meters) could not be defined. Second, water quality which refers to the state of the water quality after the collection. Third, the costs refer to the costs of the collection method in Euro's. If precise costs are not available, estimations are made. The costs for purchasing a certain machine are referred to as purchase costs. Costs for starting a collection method (without purchase) are defined as initial costs. Other costs are represented in the table per hour. Fourth, the executing authority refers to the responsible party for executing the collection, e.g. specialized firms or water authorities. Fifth, transport refers to the state of duckweed during transportation. e.g. green state or dry. Sixth the collection time refers the amount of time used during the collection, estimations are made, based on collection technique.

Last, ‘specials’ is not an actual parameter but shows special information about the collection method that can be useful.

Table 4.1. Summarizing table for duckweed collection methods and transportation in urban areas based on literature and expert opinions for different parameters (LWA: Local Water Authority).

	Parameters							
Collection methods	**Description**	**Scale**	**Water quality**	**Costs**	**Executing authority**	**Transport**	**Collection time**	**Specials**
Duckweed screens, manually	A net tied to a float, laid vertically in the water and is pulled to the side of a basin	Medium	Improved after	200 per hour	Berkhof BV	Tipper truck	Few hours	
Crane with a screen	A boat skims the duckweed from the water, utilizing a crane with netted bottom to remove the duckweed	Medium	Medium improvement after	720 initial cost +110 per hour	Loonbedrijf Harry Blokland	Truck	Few hours	Often used
Krooskarper	A boat with a V-shaped landing net	Medium	Medium improvement after	200 per hour	Firma Reijm BV	Truck	Few hours	
Special Catamaran	Two floats are connected by a conveyor belt that collects duckweed	Large	Little improvement after	125 per hour	Loonbedrijf CH. Portengen	Truck	Days	
Duckweed wheel	A conveyor belt held by two floats is used to collect duckweed, powered by solar energy	All	Little improvement after	4000+	LWA	Truck BigBags	Weeks	Unmanned Solar
Duckweed guzzler	A box connected with a pipe, creates a current in a water body to collect the duckweed into the box	Large	Improved after	20.000 purchase costs	Water authority Rijn & IJssel	Truck	Days	
Pump and culvert	An initial pump connected with a pipe	Large preferably	Improved after	2000+	LWA	Truck	Days	
Manually (nets)	Collection conducted through	Small	Improved after,	16.000 per	LWA/civilians	Truck	Days	

	the use of landing nets and a boat to reach the further ends of the waterways		separate waste by hand	season				
Proskim	Pumps the upper water layer from a small floating unit in the water to an onshore filtration unit	Small to medium	Improved after, separate waste	5000+ purchase costs	LWA	Truck	Days to weeks	New design

This section determines the most recommended collection methods, based on the above analysis. The recently designed Proskim water skimmer shows a lot of potential. While currently it does not collect duckweed so fast, in the future it could, however, become a suitable method. If the water skimmer would be further developed, especially on reducing collection time, this method would become more suitable. Furthermore, duckweed screens, manually collection and the duckweed guzzler are suitable methods according to their collection time, efficiency, scale and comfortability of collection. All methods have benefits and drawbacks, based on the place of utilization. Most important is to fit the right collection method to the site.

Low budget options

The most suitable methods for a low budget are probably the duckweed screen and manual collection methods, caused by their high efficiency and relatively low costs. But on a longer time span these manual collection methods will probably be more expensive than for example the Proskim water skimmer or the guzzler, because a skimmer and a guzzler are both methods with high initial costs and lower costs for maintenance or employments.

Long term options

For a higher budget the duckweed guzzler and Proskim would be preferred, due to the relatively large collection scales and the less manpower that is needed. Another advantage of the Proskim method is that it could be used in all possible water bodies because gradient, size or vegetation are not an issue for this method.

Conclusion

The above discussed methods are all measures developed specifically for duckweed collection. However, these methods often have high initial investments and maintenance costs which have not always been accounted for above. A second disadvantage of some of the collection techniques is their low collection efficiency which is an essential parameter to determine whether a method is useful. Thirdly, efficiency levels of each method might, also, be affected by irregular banks and the high presence of vegetation. Finally, these methods could have harmful effects on the environment and could negatively affect water quality (Maessen, 2014; Raaphorst, 2015; Nieuwenhuis and Maring, 2009).

The methods which are shown in table 4.1 and not mentioned in the low budget and long term options are not directly recommended for collecting duckweed, but might be suitable for certain specific places. In short, the manually collection methods are useful for a low budget scenario. The Proskim method and the guzzler are more feasible for a higher budget, because it requires less work and in course of time it will become less expensive than manually collection.

5. Product analysis

Many studies have, proven the capacity of duckweed to absorb nutrients, particularly, nitrogen, phosphorus, calcium, sodium, potassium, magnesium, carbon and chloride, from surrounding waters (Cheng & Stomp, 2009; Leng et al., 1995; Leng, 1999; van der Spiegel et al., 2013; Xu et al., 2012). This capacity has been investigated as a method of wastewater treatment and has been proven to be quite successful (Journey et al., 1994; Leng et al., 1995; Leng, 1999; van der Spiegel et al., 2013). However, this ability might have some drawbacks depending on toxicity levels of water basins where duckweed has grown. Heavy metals, phenols, pesticides, dioxins, and pathogens accumulation pose a great danger when further processing the duckweed, particularly when this plant enters the human food chain system (Leng, 1999; van der Spiegel et al., 2013). Therefore, depending on the contamination of the waters and subsequently the duckweed, there are different destinations for this plant. This chapter will answer sub-question 5 and give a broad description of possible duckweed derived products. It will, first, analyze water purification, which is a service provided by this plant before any other utilization, and, later, all the possible products based on contamination levels.

5.1 Water purification

Duckweed can be used as a purifier when the water is suffering from eutrophication (Niewenhuis & Maring, 2009, p.10; Xu et al., 2012, p.592). Currently, eutrophication is prevented by activated sludges which are used to remove these nutrients. Unfortunately, they are costly and technologically complex. Duckweed could help organizations to reach their water quality targets in the following way:

Due to the fast growth of duckweed, water purification can be done in the form of targeting nutrients, or be employed to reduce pollution from metals (Niewenhuis & Maring, 2009, p.32). Duckweed is relatively resistant to metals, and, therefore, able to reduce metal pollution without dying itself (Ibid.,p.32). In Figure 5.1 duckweeds tolerance levels to heavy metals are shown. Duckweed also takes phosphorus and nitrogen out of the water. The nitrogen is first converted into ammonia and then taken up by the roots. One of the benefits of duckweed is that it better adsorbs phosphorus than algae do. Duckweed can remove 30-90% of the phosphorus (Chen et al.,2012). Moreover, it transforms the nutrients in protein and starch (Zhou et al., 2015 p.550). Additionally, the duckweed roots host bacteria which further absorb waste nutrients (Nieuwenhuis & Maring, 2009, p.32). Unfortunately when the water is too polluted, this purifying function has the consequence that the excess duckweed cannot be used as food or feed. The heavy metals could affect the metabolism of organisms.

Purification could be used in both open and closed (waste) water systems (Niewenhuis & Maring ,2009 p.33). For example, in a purifier or ditches. The excess duckweed can be collected and used for bio energy. Another benefit is that there is almost no processing of the duckweed needed; it can be used wet.

5.2 Uncontaminated duckweed

In the last years, researchers have turned their attention to duckweed in light of new challenges posed by a growing population, the increase in consumption of animals protein registered in the last decades, and the impact of the human food system on the environment (Leng, 1999; van der Spiegel et al., 2013). Animal protein consumption accounts for up to 40% of the total human intake and the

Food and Agriculture Organization (FAO) foresees a rapid increment by 2050 following the current trends (Leng, 1999). Given the above challenges, there is a growing need to introduce novel products, such as duckweed, for the production of animals proteins that are cheaper, healthier and more sustainable (van der Spiegel et al., 2013, p.2).

It is of great relevance to take into consideration the protein output per hectare of duckweed in comparison with currently used plant protein sources for both feed and food, such as soy, grains and legumes. Literature studies on dry weight duckweed report up to 3000 Kg/hectare/year of protein contents (Cheng & Stomp, 2009; Journey et al., 1994). In contrast, protein production of other crops is much lower ranging from 300 Kg/hectare/year for soybean to 70 Kg/hectare/year for rice and 180 Kg/hectare/year for maize (Cheng & Stomp, 2009). For these reasons, duckweed seems to be a viable option to be considered when addressing alternative protein sources and new strategies to foster food security (Leng, 1999).

The high protein content of duckweed renders it a promising replacement of soybean in animal feed products. Protein content of dry biomass can be between 15% and 45%, depending on species, strain with species and growing conditions (Cheng & Stomp, 2009; Xu et al., 2012). Particularly, it has been found that duckweed can reach around 40% of protein with a high biological value in water basins with 10-30 mg NH3-N/litre (Leng et al., 1995, p.7). These values are similar to protein contents yielded by soybean, which range between 33 and 49%, also depending on species and growing condition (Cheng & Stomp, 2009). High protein values pertain that amino acids qualities contained in the plant closely reflect the necessary requirements for animal consumption (Cheng & Stomp, 2009; Xu et al., 2012). Table 5.1 compares amino acid contents of three duckweed species, *S. polyrrhiza, S. punctata, and L. gibba*, rice, corn gluten meal, peanut, soybean meal and milk with protein requirements for chicken feed.

Table 5.1. Amino acid composition of bulk protein of Lemnaceae species, grains, legumes, and casein (Cheng & Stomp, 2009)

Amino Acids	*L. gibba*[a]	*S. punctata*[a]	*S. polyrrhiza*[a]	Green Grass[b]	Soybean Meal[b]	Peanut[b]	Rice[b]	Corn Gluten Meal[c]	Casein[b]	Recommended Levels of Essential Amino Acids for Chicken Feed[c]
	g/100 g protein									
Leu	7.15	6.88	6.85	10	8.0	6.7	8.2	15.3	10.0	7.5
Ile	3.87	3.76	3.75	5	6.0	4.6	5.2	4.9	7.5	5.0
Val	4.96	4.71	4.40	5	5.3	4.4	6.2	5.1	7.7	5.0
Met	0.83	1.07	0.83	2.5	1.7	1.0	3	2.35	3.5	2.0
Cys	NA[d]	NA	NA	2.0	1.9	1.6	1.3	1.65	0.4	3.6[e]
Phe	4.45	4.38	4.20	5–6	5.3	5.1	5.0	5.6	6.3	4.4
Tyr	2.91	3.14	3.05	5.0	4.0	4.4	5.7	2.3	6.4	6.4[f]
Lys	4.13	4.26	4.30	5.5	6.8	3.0	3.2	1.85	8.5	4.0
Thr	3.20	3.31	3.45	5.4	3.9	1.6	3.8	3.0	4.5	3.5
Trp	NA	NA	NA	2.2	1.4	1.0	1.3	0.5	1.3	1.0
His	1.89	1.90	2.15	2.0	2.9	2.1	1.7	2.1	3.2	1.9
Arg	4.29	4.86	5.25	7.0	7.3	11.3	7.2	3.25	4.2	5.0
Ser	2.61	2.83	2.80	5	4.2	NA	NA	NA	3.3	NA
Pro	2.93	2.95	3.28	NA	5.0	NA	NA	NA	13.1	NA
Gly	3.79	3.93	3.95	NA	NA	5.0	NA	NA	2.1	NA
Glu	7.60	7.69	8.00	11.5	18.4	17.7	NA	NA	23.0	NA
Asp	7.12	7.38	7.55	5.3	NA	NA	NA	NA	7.0	NA

[a] Rusoff et al. [38];
[b] Block and Bollings [49];
[c] Scott et al. [50]; laying hen requirement;
[d] Not available;
[e] Sum of phenylalanine and tyrosine;
[f] Sum of phenylalanine and tyrosine.

Through the analysis of table 5.2, it is evident that the content of amino acid in duckweed species are lower than the ones contained in soybean meals. On the other hand, many researches have indicated the high impact of growing conditions on percentage of proteins present in these plants, with values increasing from to 25% up to 50% per individual amino acid (Cheng & Stomp, 2009). In addition, larger yields harvested that the duckweed is able to produce, render this plant highly competitive (Leng et al., 1995; Leng, 1999).

Finally, one last element need to be taken into account when considering duckweed as a possible protein source for animal feed and human consumption: toxicity. Firstly, in addition to the contaminants such as heavy metals, phenols, pesticides, dioxins, and pathogens, it has been noted that significant levels of oxalic acid can be found in the genera *Spirodela* and *Lemna*, both in crystallized and soluble forms. This compound might be toxic to animals when ingested in high concentration, although no studies have shown contraindication given by duckweed animal feed containing oxalic acid (Cheng & Stomp, 2009; van der Spiegel et al., 2013). Concerning human consumption, calcium oxalate contents of duckweed need to be monitored to highlight any possible toxicity. However, recent studies have argued that oxalate helps urinary excretion particularly in individuals suffering from stones (Cross, 2011). For these reasons, duckweed collected for urban waterways might not be suitable for either animal feed or human food as these types of outcomes can only be achieved from plants cultivated in highly controlled settings (Maessen, 2014).

5.2.1 Feed

Duckweed could be a viable source to produce feed and feeding supplement for animals. Many studies have been carried out regarding animals such as fishes, dairy cows, pigs, sheep, goats and poultry, and have shown that proteins intake can be partially or totally substituted by duckweed without impeding growth (Cheng & Stomp, 2009; Journey et al., 1994; Xu et al., 2012).

Fish

Duckweed as fish feed is the most widespread utilization of this plant, since it can be used in a green state and is very suitable for both herbivorous and omnivorous animals (Iqbal, 1999, p.57; Journey et al., 1994, p.18). Commonly, protein feed with high biological value are very expensive and cannot be supported by fish farming. Duckweed is locally available and a low cost solution for fish intensive aquacultures (Leng et al., 1995). Many studies have demonstrated that tilapia and carps farms can be sustained with the use of duckweed balancing feed, fertilizers input, fish density and oxygen (Cheng & Stomp, 2009; Iqbal, 1999, p.57; Journey et al., 1994, pp.18–19). Other pilot experiments have shown that a dietary inclusion of *Spirodela polyrrhiza* up to 30% is efficiently converted into live-weight as displayed in Table 5.2 (Balogun & Fagbenro, 1995, p.316). More recent researches have indicated that a diet containing sole duckweed might be too low in carbohydrates and fats content, thus, suggesting a combination of 50/60% duckweed with 50/40% of carbohydrates and fat rich feed for a balanced diet (Iqbal, 1999, p.58).

Table 5.2. Response of Tilapia and feed utilization of duckweed (Balogun & Fagbenro, 1995)

Performance indices	Diets					
	Control (0%)	5%	10%	20%	30%	100%
Initial weight (g)	13.5^{a}	13.4^{a}	13.9^{a}	14.4^{a}	13.5^{a}	14.3^{a}
Final weight (g)	52.7^{a}	49.4^{a}	48.9^{a}	47.9^{ab}	43.0^{bc}	22.5^{d}
Survival (%)	97.7^{a}	95.5^{a}	95.5^{a}	100.0^{a}	97.78^{a}	95.56^{a}
Weight gain (%)	294.5^{a}	269.7^{ab}	251.8^{ab}	233.5^{abc}	281.5^{bc}	129.4^{d}
SGR (% day^{-1})	2.44^{a}	2.4^{a}	2.4^{a}	2.2^{a}	2.1^{a}	0.8^{a}
DFI (g day^{-1})	1.14^{a}	1.2^{a}	1.2^{a}	1.1^{a}	1.0^{a}	0.6^{b}
FCR	1.6^{a}	1.8^{ab}	1.8^{ab}	1.9^{ab}	2.0^{ab}	4.3^{c}
PER	2.1^{a}	1.8^{a}	1.8^{a}	1.8^{a}	1.7^{a}	0.8^{b}
PPV	7.6^{a}	7.1^{a}	6.6^{a}	6.6^{a}	6.9^{a}	3.9^{b}

Poultry

Duckweed has also been widely recognized to have a great potential in poultry diets. It could replace alfalfa (Lucerne) as a protein source (Leng et al., 1995, p.9). Birds fed with up to 25% of dehydrated duckweed have shown a greater increase in weight gain than those fed with conventional meals (Iqbal, 1999, p.59; Leng et al., 1995, p.9). Furthermore, the high content of carotene and the pigment xanthophyll reflects within eggs yolks color and nutritional values (Iqbal, 1999, p.54). Table 5.3 shows weight increase and egg quality in poultry fed with duckweed meals.

Table 5.3. Production levels of egg-laying birds at 18 weeks on conventional base diet containing varying proportions of dehydrated Lemna gibba meal (33% N x 6.25 in DM). Metabolizable energy and protein intake were consistent across treatments (Leng et al., 1995)

	Level of dehydrated duckweed, %		
	0	25	40
Feed consumption (g/d)	131	131	125
No of eggs/ week/ hen	5.9	5.9	5.6
Mean egg wt (g)	64.2	63.1	63.6
Feed conversion (g DM/g egg)	2.41	2.47	2.38
Live weight gain (g)	40	114	-118

Various studies have indicated different responses depending on the different *Lemnaceae* used as substitute and their protein/fiber ratio in chicken diets (Iqbal, 1999, p.60; Leng et al., 1995, p.9). It has been demonstrated that increasing the percentage of dried duckweed integration within young broiler chickens' diets negatively impacts their growth, while older birds maintained significant weight gains (Haustein et al., 1992, p.334; Leng et al., 1995, p.9). Therefore, care is required when integrating duckweed within younger chickens feed.

There is evidence from Taiwan and Bangladesh that ducks, instead, can eat fresh duckweed readily fed or directly collected (Iqbal, 1999, p.60). Furthermore, Men et al. demonstrate how duckweed is a viable substitute of soybeans in duck farming as shown by Table 5.4. Common ducks are unaffected in their growth rate and this solution is believed to reduce the costs of feed by at least 13% (Men et al., 2001, p.1746).

Table 5.4. Daily weight gains of common ducks fed increasing percentage of duckweed as replacement for soybeans (SB) (Men et al., 2002, p.1744)

Item	SB100	SB70	SB55	SB40	SB0
Live weight, g					
Initial	859	851	830	859	842
Final	1,771	1,869	1,882	1,807	1,806
Daily weight gain, g	26.1	29.1	28.3	27.1	27.6
Feed conversion, kg DM/kg gain	3.63	3.71	3.82	3.89	3.88
ME/gain, MJ/kg	55.0	51.1	52.6	53.3	52.1
CP/gain, g/kg	654.7	779.0	761.8	760.7	650.0

Swine

In regards to swine feed, the information available from literature is highly contradictory (Iqbal, 1999, p.59; Leng et al., 1995, p.10). Which could be explained by little available research. Yet, farmers in many countries have incorporated duckweed to swine meals (Leng, 1999). Haustein et al. (1992), as quoted by Leng et al. (1995, 1999) and Iqbal (1999), report a significant decrease in live weight gain with an increase of fed duckweed. However, it is necessary to take into consideration that in this pilot the quality of duckweed was poor (23% proteins and 7.5% fibre content), the toxicity level was not tested and the young age of the animals might have played a role (Leng, 1999). Van et al. (1997) and Hang (1998) show that replacing 7% of the dried matter of the swine meals constituted by sweet potato vines with 5% duckweed at a green state, live weight gained is greater (see Table 5.5). Many authors agree on the necessity to further research in regards to duckweed integration into swine feed, particularly in regards to the possibility of using freshly harvested duckweed rather than dehydrated (Hang, 1998; Iqbal, 1999, p.59; Leng et al., 1995, p.10; Leng, 1999; Van et al., 1997).

Table 5.5. Mean values for growth rate and feed conversion in pigs fed conventional (control) diet and duckweed at a green state replacing the sweet potato vines (DW) (Hang, 1998).

	DW	Control
Liveweight, kg		
Initial	20.3	19.0
Final	86.31	67.5
Daily gain	0.552	0.404
DM feed conversion	3.66	4.50

Ruminants

As for pigs, there is not an abundance of studies in regards to ruminants, although, some researches have been carried out for cattle and sheep (Iqbal, 1999, p.60; Leng et al., 1995, p.10). Leng et al. (1995) argue that duckweed may not make a substantial contribution to the amino acid absorbed by the animals since proteins might be fermented in the rumen and difficult to be protected from digestion in the first stomach. Nevertheless, research conducted to date show the great potentials of duckweed integration within ruminants' meals. Russoff et al. (1977, 1978), as reported by Iqbal (1999), found that duckweed did not alter the taste of milk in Holstein calves. Furthermore, cattle fed with a mixture of 67% duckweed and 33% corn almost doubled their daily weight gain, from 0.5 Kg to 0.94 Kg (Iqbal, 1999, p.60). Finally, it has been hypothesized that approximately 3 ha of duckweed cultivation could feed up to 100 dairy cows and increase their milk production (Iqbal, 1999, p.60; Leng, 1999). All these studies have been performed using dried duckweed.

5.2.2 Food

In Myanmar, Laos and northern Thailand the duckweed specie *Wolffia arrhizal* is part of the traditional local diet and is considered very nutritious. It is considered a food for "poor men" and is cultivated mainly in rural environments (Iqbal, 1999, p.56; Leng, 1999). Duckweed has been a valid source of minerals and green vegetables in these regions, particularly throughout the dry seasons when such resources are very scarce (Leng, 1999). Remarkably this practice has not spread to other areas of the world. This may be because of the high content of oxalic acid in some species of duckweed affecting its taste, and the difficulty in separating worms, snails, protozoa, and bacteria from this aquatic plant (Iqbal, 1999, p.56).

Duckweed proteins and its amino acid contents closely reflect animal proteins. Based on FAO nutrition recommendation, duckweed, considering its contents of lysine and methionine, could be a viable complement to grains diet in human consumption especially in regions where there is a deficiency in proteins intake (Table 5.6)(Iqbal, 1999, p.56; Journey et al., 1994, p.13; Leng, 1999).

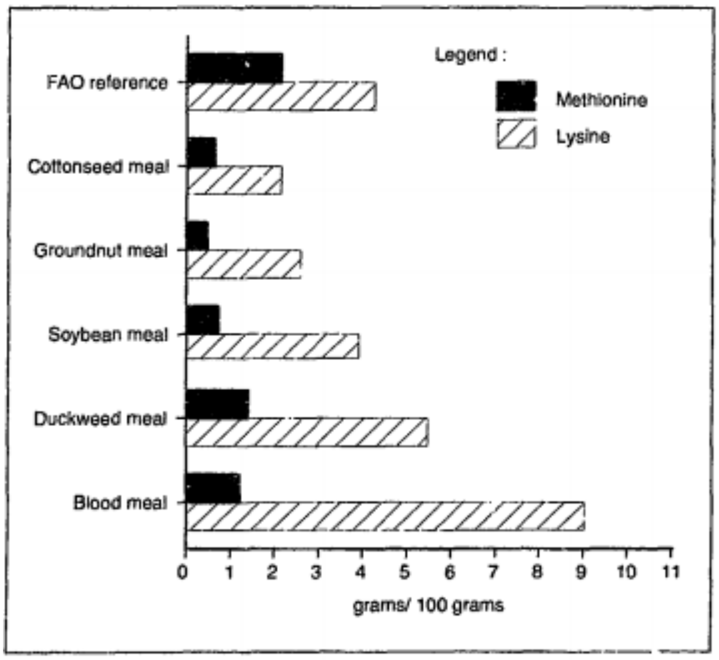

Figure 5.1. Comparison of lysine and methionine content of protein of various sources (Iqbal, 1999)

Furthermore, duckweed has been reported to be rich in vitamins containing around 40 different types, notably A, B1, B2 , B6 , C, E, and PP. The two latter vitamins are particularly high ranging from 20 ppm to 60 ppm (Iqbal, 1999, p.56).

5.3 Mildly contaminated Duckweed

In the previous section human food and animal feed were discussed as products made from duckweed. While these are interesting options for duckweed usage, they require non-contaminated duckweed produced in human controlled settings. Since this research focusses on duckweed grown in urban settings, waters are not always as pure and controlled as needed for food and feed (Fakhoorian, 2015; Ten Haven, 2015). Yet this does not necessarily render the duckweed useless. Therefore, this section will focus on possible products of duckweed stemming from mildly contaminated water and duckweed.

5.3.1 Fertilizer

The *lemna aoukikusa* and *lemna minor* type of duckweed can be used as fertilizers (Suzuki et al., 2014). They are host to the *cinetobacter calcoaceticus* P23, a plant-growth promoting bacteria. Artificial fertilizers are only available to a limited extend Hence, natural fertilizers can help meeting the demand for fertilizers. These bacteria have a growth stimulating effect on duckweed, yet it is unknown whether they affect other plants. Oron shows that duckweed cannot only be used as fertilizer, but argues that the water it has purified can be used for irrigation of agricultural crops (1994, 28-29). Figure 5.2 shows the influence of duckweed in the nitrogen cycle, which is important as nitrogen enhances plant growth.

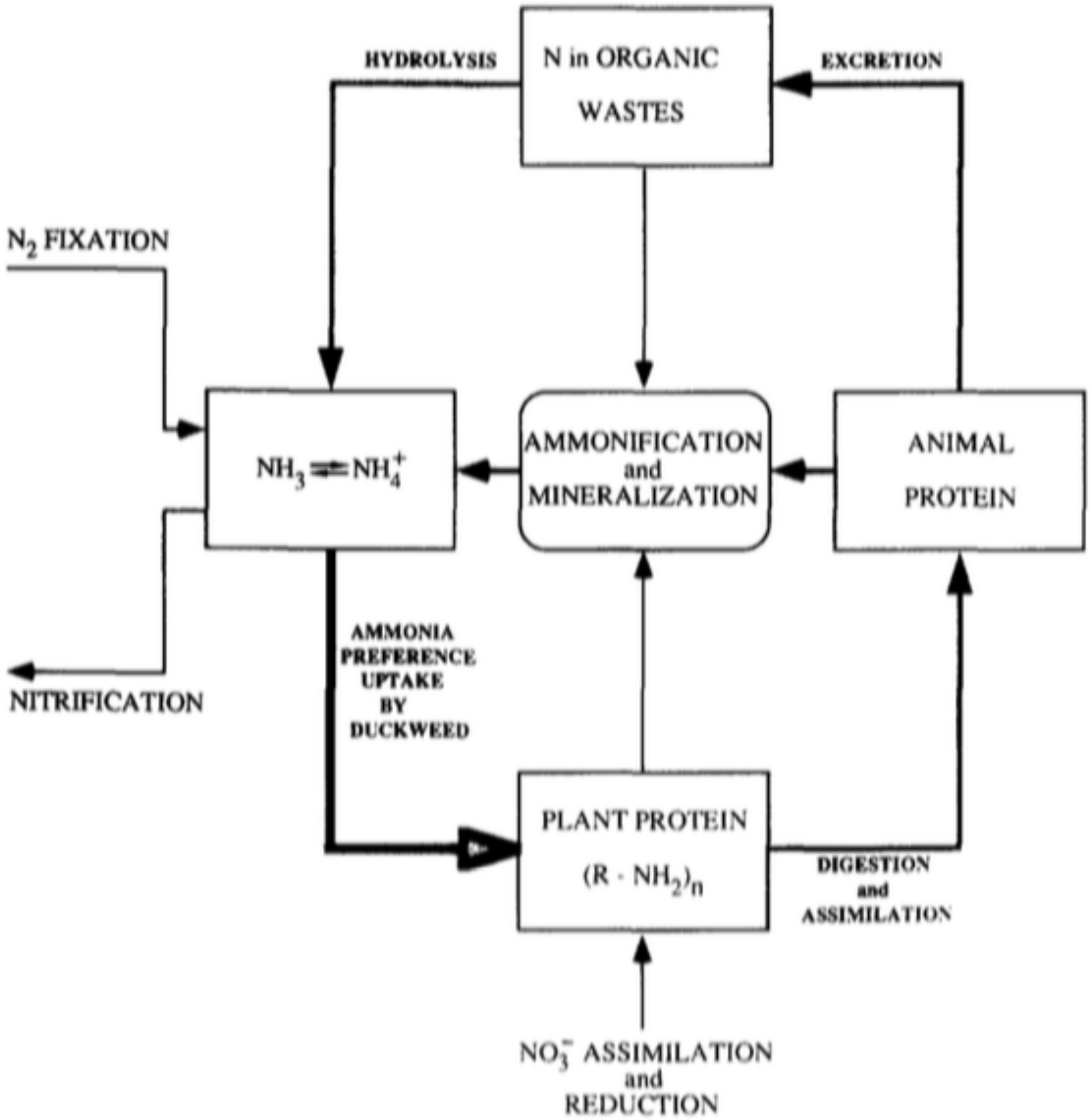

Figure 5.2. The role of duckweed in the nitrogen cycle (Oron, 1994)

Duckweed as fertilizer is practically unknown in the scientific community. As far as the literature review showed, hardly any research has been conducted regarding duckweed as a fertilizer. Yet some practical applications have been found as Tamra Fakhoorian uses mildly contaminated duckweed as fertilizer, and argues that the level of nitrogen in duckweed is important if one wants to use it as such. Based on her expert opinion it is best to use the duckweed in the green state as it is less costly and reduces the processing. However it can be air dried to 40-60%, the remaining 40% would still have to be dried. In the green state, the duckweed has to be used as an outside fertilizer as inside it will mold. After the collection it can be spread out on the land. Depending on the nitrogen level, the farmer might need to add extra nitrogen. All in all, it is strongly advised to conduct further research in this field.

5.3.2 Soil quality enhancement

Duckweed can be used to enhance soil quality through composting, and specifically through vermicomposting, i.e. composting conducted by worms, with the help of *Eisenia fetida* earthworms (Kostecka & Kaniuczac, 2008). In Kostecka & Kaniuczac's experiment compost pots of solely duckweed and a combination of duckweed and manure were compared (2008). L. minor stems from municipal wastewater. As a result, the sole duckweed pots contained fewer worms, which are needed for efficient composting. However, the difference could be influenced by the experimental conditions (Ibid.). The duckweed used in the experiment was dry. When green state duckweed had been used, the nitrogen and phosphorus level was higher than composts. Moreover, Lot et al. (1979 in Iqbal, 1999,p.61), Tai-hsingh et al. (1975 in Iqbal, 1999, p.61) and Welwitsch (1859 in Iqbal, 1999, p.61) found that the application of duckweed on soils led to better soil texture and better water and cation exchange, the soil capacity to exchange positive ions with the soil solution. Again, few scientific articles on this subject exist and therefore practical examples will be used. There is a patent stemming from 2002 of Kyle et al. on a technology to purify water with duckweed and use the duckweed to make pulp that enhances soil quality. After treating the wastewater, the duckweed is collected and turned into pulp by mixing the green state duckweed with a shredded paper (Kyle et al.,2002). After creating the pulp, it can be used as a biodegradable delivery package. which can later on enhance the soil.

5.4 Highly contaminated Duckweed

As explained earlier, it is possible to use contaminated duckweed for material or energy production. Of course, the duckweed does not have to be contaminated to be used for the purposes that will be introduced below. All duckweed is suitable for transformation in these products.

5.4.1 Bio-energy

This first possibility for contaminated duckweed is transformation into energy resources. Verma & Sunthar have constructed an overview (figure 5.3) of various available forms of energy resources and the processes required for transformation (2015, p.5). The transformation process starts with the duckweed biomass. Some studies indicate that the larger types of duckweed such as S. punctate, L. gibba, L. minor, are more suitable for biomass production (Xu et al., 2012, p.592).

After duckweed collection there are three main paths identified by Verma & Sunthar (2015, p.5): hydrothermal processing/upgrading and liquefaction, thermo-chemical conversion, and bio-chemical conversion, all of which will be explained in some detail below, and will lead to different outcomes. Simultaneously, the different processes demand different duckweed. Wet duckweed can be used for hydrothermal processing, while dry duckweed is more suitable for thermo-chemical and biochemical conversion. Table 5.6 by Verma & Sunthar gives a first crude overview of the costs and development status of the various techniques required in the different transformation processes.

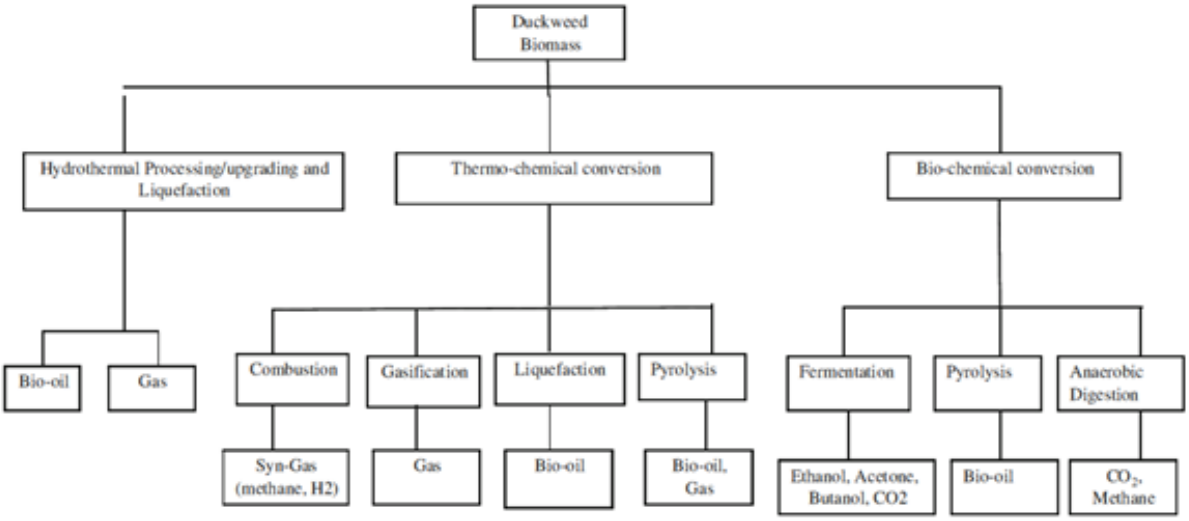

Figure 5.3 Possibilities for duckweed to energy conversion (Verma & Suthar, 2015, p.5).

Table 5.6. Different duckweed processes and applicability (Verma & Suthar, 2015, p.4).

Techniques	Cost of treatment	Environmental paybacks	Advancement require	Development stage	Remarks
Anaerobic digestion	Low/moderate energy	Biogas generation	Sludge pre-hydrolysis required to enhance biogas generation	Successfully applied at full-scale	Release of phosphate and ammonia during digestion process
Incineration	High	Energy generation minimization of biosolids quantity	Mechanical dewatering, drying, use of waste heat	Full-scale	Phosphate can be recovered from ash
Coincineration in coal fired power plant	High/moderate	Energy generation, beneficial use of inorganics	Mechanical dewatering, drying, use of waste heat	Full-scale	Relative amount that can be co-incinerated is limited
Pyrolysis and gasification	High	Valuable products recovery, minimization of biosolids quantity	Mechanical dewatering, drying, use of waste heat	In development stage	Complex process, marketing of products needs attention
Wet air oxidation	Moderate	Improvement in dewatering properties of sludge	Optimization	Applied globally in practice	Process primarily focused on sludge dewatering
Supercritical water oxidation	High	Energy generation, minimization of biosolids quantity	Reactor concept, process performance	In development stage	Complex process corrosion and scaling problems of the reactors walls
Hydrothermal treatment	Moderate	Biogas generation, production of valuable carbon resource or denitrification, minimization of biosolids quantity	Process performance	Practical experience limited	Removal of heavy metal can be included

Hydrothermal conversion

In cases of wet duckweed, the aquatic plant can be used in hydrothermal processes where the duckweed is put in pressurized heated water. Depending on the pressure and temperature, it is possible to extract biofuels via liquefaction, or biogas via gasification (both techniques are explained below in the thermochemical conversion discussion) (Tekin, Karagöz, & Bektaş, 2014, p.677).

Unfortunately, Verma & Sunthar indicate that experience with these practices for duckweed are limited (2015, p.4).

Thermochemical conversion

Dry duckweed can also be thermochemically processed, meaning that heat is used to turn the duckweed into fuels or gases. Dry duckweed can always be incinerated for heat. However, also different thermochemical procedures such as gasification, liquefaction, or pyrolysis exist and might be more useful. Thermochemical gasification and liquefaction are used in a similar way for hydrothermal processes. When gasification is used (figure 5.9), the duckweed is heated to such a high level that either syn-gas or producer gas can be produced (Huber, Iborra, & Corma, 2006, p.4052). While producer gas is mostly used for electricity or heat, syn-gas is mainly used for processing into different fuels and products (Ibid., p.4052). Figure 5.4 shows a few of these product possibilities. The gasification process can be enhanced by using solar powered gasification techniques, since it decreases the amount of burned biomass needed in order to reach the heat levels required for the gasification process (Ibid., p.4055). Regarding liquefaction, a study by Xiu et al. argues that duckweed liquefaction can be used for bio-oil production (2010, p.1294-1297). By concentrating the duckweed through a shaker and by then heating it between 260 and 340 degrees Celsius for 60 minutes the highest oil production results can be reached (Ibid., p.1294-1297). 340 degrees seems to be the maximum temperature for maximum oil yield, and using a catalyst reduces the oil yield. Xiu et al. analysis indicated that the oil yielded from this process was of good quality, of around 33.95 MJ/kg (with a deviation of 1.79 MJ/kg), and of better quality than oil produced from manure or feedstock (Ibid., p.1298). Similarly, pyrolysis can be used. This process involves the heating of duckweed with a lack of oxygen, thus preventing it from combusting, turning it into gas and/or bio-oil (Huber, Iborra, & Corma, 2006, p.4052).

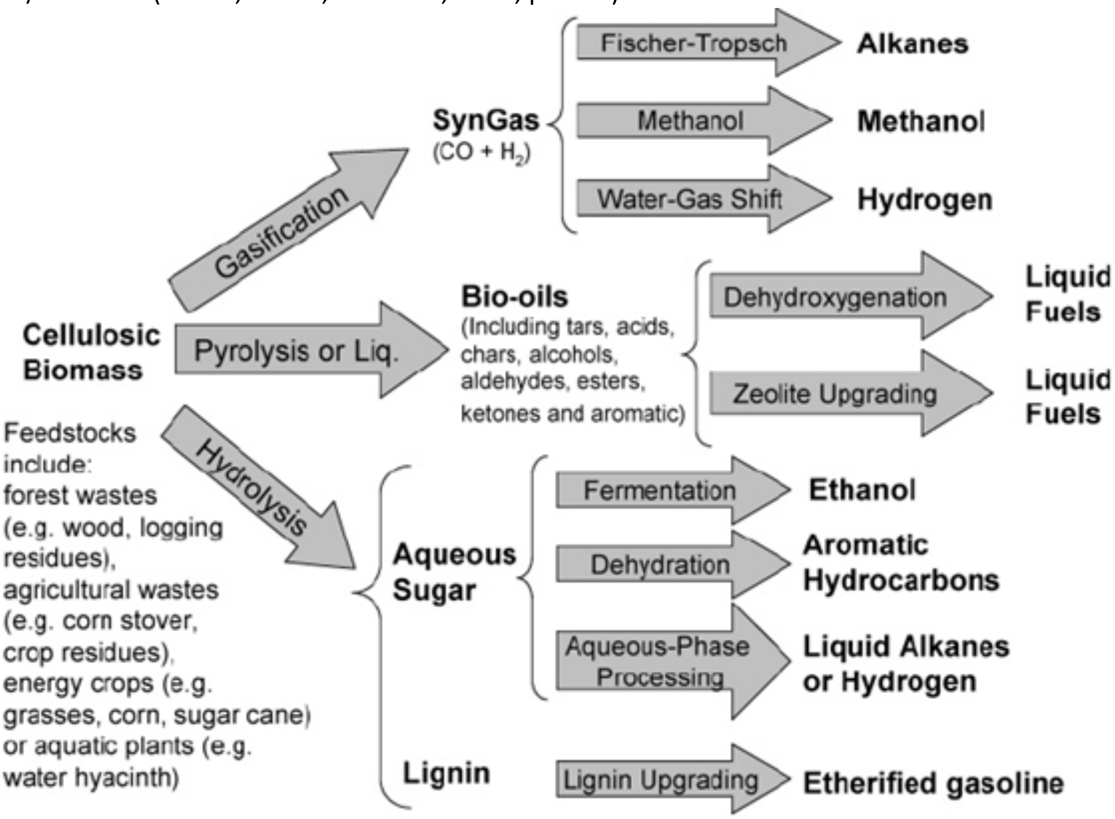

Figure 5.4. Different processes to bio-energy identified by (Huber, Iborra, & Corma, 2006, 4047).

Biochemical conversion

The third path is biochemical conversion (2015, p.5). In biochemical conversion, biochemistry (the study and use of the chemistry of biological processes) are used, is used to break down the duckweed to useable energy (Woods and Hall, 1994). When biochemical processes are used on duckweed for energy production, some remarks have to be made.

Firstly, the usefulness of duckweed for bioethanol depends on the starch content of the duckweed. The more starch, the more bioethanol can be produced. Various studies found this starch content varied between duckweed species and circumstances from 3 to 75% of its dry weight (DW) (Xu et al., 2012, p.591). The starch in duckweed increases when its growth environment is not optimal (Ibid. p.591). Thus, duckweed can be manipulated to increase starch levels. This can be achieved by, for example, depositing freshly harvested duckweed into nutrient-poor water leads to nutrient-stress of the duckweed, to which the duckweed responds by producing starch to store glucose (Ibid., p.595). Another method might be to use temperature differences because they are expected to increase starch levels because lower temperature leads to a lower respiration level (Xu et al., 2011, p.70). Furthermore, it is also possible to increase starch production by increasing the salinity of the water (Xu et al., 2012, 598) or by using certain chemicals such as abscisic acid, cytokinin, 2-aminoindan-2-phosphonic acid (Ibid. 595).

The starch can then be transformed into other products such as bioethanol. This can be done via, for example, hydrolysis functions similarly to the saccharification (breaking carbon molecules down to sugars) of corn (Xu et al., 2012, 596) followed by fermentation. Cheng & Stomp showed, for example, a fermentation process “using a-amylase (Sigma A3404), pullulanase (Sigma P2986) and amyloglucosidase (Sigma 10115)” that transforms the sugar into ethanol (Cheng & Stomp, 2009, 24). Another example is provided by Xu et al. who argue that it is also possible to use an enzymatic hydrolysis (breaking down of molecules to sugars with enzymes), for example by using the Megazyme Total Starch Assay Procedure (Megazyme, 2014), “for duckweed saccharification” (Xu et al., 2012, p.597). They then use “Saccharomyces cerevisiae (ATCC 24859) […] for ethanol fermentation” in order to transform the sugars into ethanol. (Xu et al., 2012, p.597). Xu et al. report that studies found that the created ethanol levels to be around 96,2 % (w/w) of what they state to be the theoretically maximum amount of ethanol (2012, p.597). It is also possible to create butanol. Using acidic hydrolysis and fermentation with *C. acetobutylicum CICC 8012*, for example, leads to a higher butanol production than when using corn (Li et al., 2012, as found in Cui & Cheng, 2015, p.21).

Another option using biochemistry can be found is reported by Cui & Cheng (2015, p.21). They report that studies of Clark (1996), Triscari et al. (2009), and Huang et al. (2013) indicate when some duckweed biomass is added to the input, such as manure, for anaerobic digesting, the production of biogas increases substantially (Cui & Cheng, 2015, p.21). Thus duckweed could be used as an enhancing product as well. Concluding, there are many possibilities for the transformation of biomass into energy resources.

5.4.2 Bioplastics

An additional option for the transformation of duckweed into products is bioplastics. This requires that dry duckweed is processed in such a way that its proteins and starch can be converted into polymer (Zeller, Hunt, & Sharma, 2013, p.376-385).Because of the high starch content duckweed could potentially be a useful product for the bioplastics industry. An info sheet by Bolch & Bos states that using extrusion, starch can be converted into thermoplastic starch (THS) (2011, p.1). The quality of the THS can be improved by adding additional materials such as plasticizers, to its composition, but this is not absolutely necessary (Bolck & Bos, 2011, p.1). The THS can than via various production methods be changed into a plastic end-product (Ibid., p.1).

Zeller, Hunt, & Sharma argue in their research that duckweed can indeed be used as bioplastics (2013, p.381). Duckweed bioplastic "was comparable with other bioplastic materials, and with high protein raw duckweed material, or material which has been refined significant gains in material properties may be achieved" (Ibid., p.381). This means that duckweed has a large chance of becoming a useful bioplastic in the near future (Ibid., p.381). However, their experiment showed that the duckweed was less useful than other materials because their research also indicated that there is a difference in the purity of the material between duckweed grown in controlled waters vis-à-vis duckweed grown in uncontrolled waters (Ibid., p.381-385). Some heavy pollutants taken up by duckweed from public waters should not end up in the plastic, therefore it is important to filter these pollutants out of the duckweed. How that can be achieved, however, is outside of the scope of this research.

5.5 Synthesis

Duckweed can be turned into many products. The flow-chart below (Figure 5.5.) sketches the main possibilities this research found from the moment duckweed is collected to the end product. Depending on the level of contamination, it's dry or wet state, and the availability of processing methods, different products can be created. It is always possible to use duckweed for water purification. It needs to be collected in order to be effective, otherwise the pollutants will just re-enter the system. It is unlikely that human food can be produced from the urban waters in The Netherlands because the contamination levels are likely to be too high. Feed is more likely, however, depending on the strictness of the legislation and the ability to remove pollutants from the duckweed. Duckweed as fertilizer or soil enhancement has not been researched extensively, but is believed to be possible, both dry and wet. Additionally some research points in the direction of duckweed as soil enhancer through composting. While it is slightly less effective as manure composting, duckweed provides an odorless option. However, more scientific research is needed on these subjects. Finally it is always possible to turn duckweed into energy or plastics. Yet, the quality of the products is determined by the makeup of the duckweed. Some products have a higher added value than others. For example, turning duckweed into electricity is less valuable than using it to removing pollutants or phosphates or turning it into human food because the added value of the latter options are higher compared to the added value of electricity. The choice what kind of product is chosen, is therefore not only a technical one, but also economical. The exact benefits of these different processes will have to be analyzed in another study in order to determine what the most efficient options for duckweed processing are for different situations.

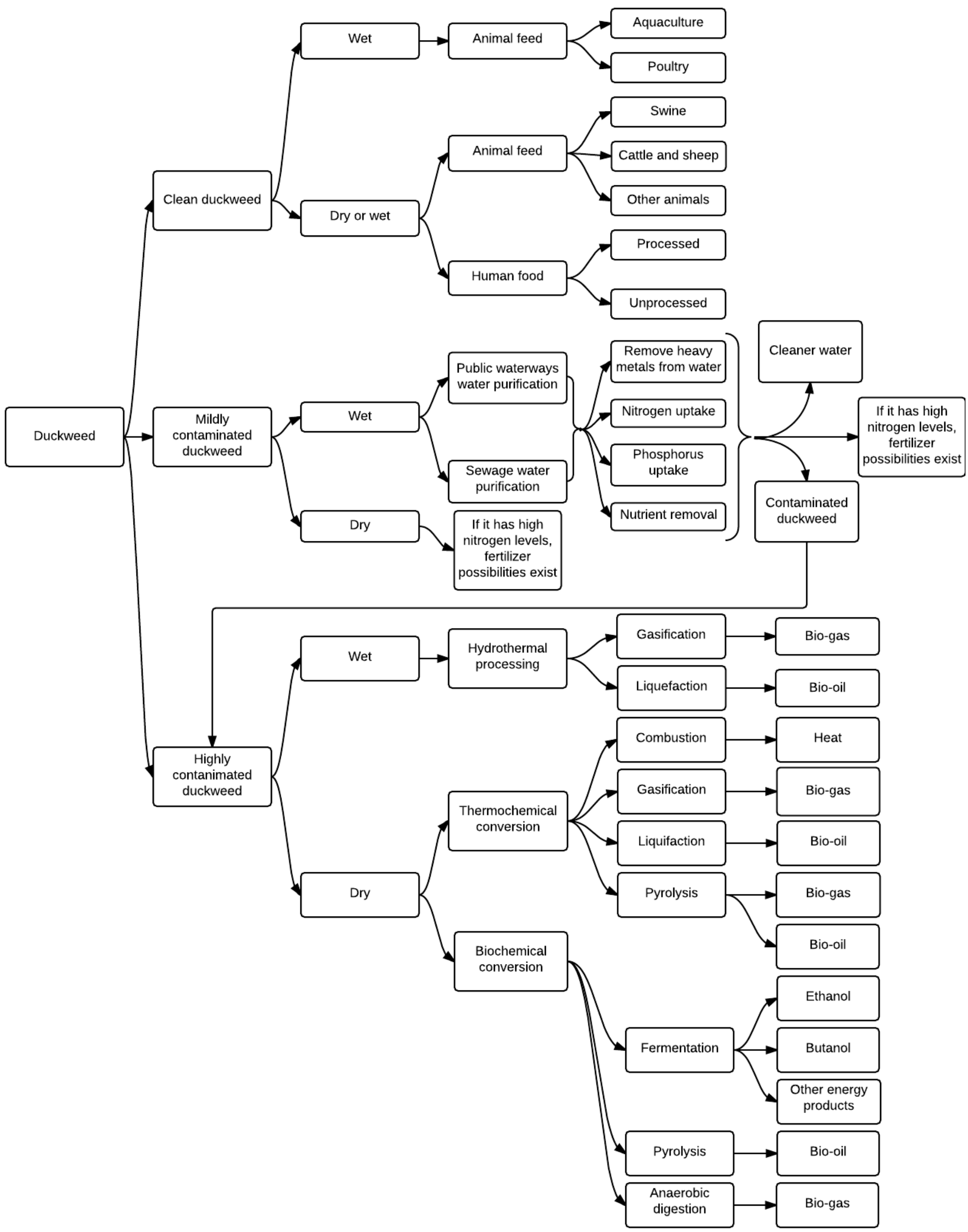

Figure 5.5. A flowchart of the duckweed product possibilities

6. Transition management and duckweed

Following the transition pathway methodology of Foxon et al., in this section sub-question 6, *how the niche market of duckweed can transition into the mainstream market,* will be answered by performing a market analysis, working from the macro to micro level, hence, starting with landscape, followed by regime and niche (2010, p.1205-1208).

6.1 Landscape

6.1.1 Legislation

Maessen stated that there is no common legislation regarding the use of duckweed (2014, p, 21). However, as this plant can be processed and used as a compound of different products, the legislation that applies to each specific field of application can be discussed.

Water purifier

Using duckweed as water purifier would help to attain the goal of the European Nitrogen Directive to ensure ecological quality of surface waters (EU, 1991) and the European Kaderrichtlijn water (EU Directive 2000/60/EG). A possible obstacle is that duckweed can only be used in a limited proportion as too much duckweed will cause the demise of other organisms (WB 21; Natura 2000). Additionally, Nature 2000 sets rules for monocultures. In case of purification, duckweed would be grown as a monoculture and therefore Natura 2000 provides a practical limitation.

Food and feed

Duckweed used for food and feed needs to meet strict standards starting with the fact that the duckweed has to be uncontaminated (Maessen, 2014). As this research focusses on urban duckweed from urban waters, which is often contaminated, it will be hard to use the urban gathered duckweed for food and feed (Derksen & Zwart, 2010). An additional limitation is that it is considered as an agricultural product which also prohibits it use as human food (Rijksoverheid, 2013A). The only possibility to convert duckweed into animal feed is when it is grown in a highly controlled setting as is currently done on sustainable farms as ECOFERM (Van Westreenen, 2013). Therefore, these two product groups are not considered in this market analysis. If these products are to be made from duckweed, then it would better to use carefully cultivated duckweed in closed water systems.

Fertilizer and soil enhancer

According to Maessen duckweed falls under the category of ‘remaining organic fertilizer’, meaning the duckweed cannot otherwise be specified (2014, p.22). Accordingly, some limitations apply to the usage. This type of fertilizer cannot be applied to pastures during the grazing season. When the land is used for animal feed production, it can only be used until three weeks before the harvest. Within land employed for vegetable and fruit production (trees not included), this plant cannot be used during the growth phase of the fruit and on less than 10 months before the harvest of fruit and vegetables that come into direct contact with soil. Further, duckweed as fertilizer cannot be used:
- “when the upper level of the soil is saturated with water;
- from September 1st until January 31st when the soil is not simultaneously irrigated;
- there is a slope of 7% or higher;
- on arable land with a slope of 18% or higher”(Maessen, 2014, p.23).

Bioplastics
Most importantly regarding bioplastics is the possibility of transfer of contaminants from the bio-plastic to the food product which is packed (Rijksoverheid, 2015A). Plastic derived from bio starch has a higher risk of contamination than conventional plastic stemming from oil. The current challenge will be meeting the standards for the packaging of food from the EU Directive 1935/2004/EC and EU directive 10/2011/EC, substances that have influences on the food are not allowed to be used (EU directive 10/2011/EC, p.22). For other products the regulation is less strict as it does not pose a direct effect on the human health.

Bio-energy
The Dutch government promotes a transition to biofuels and therefore a lot of limitations have been removed in 2013, making the development of biofuels easier as more organic material is allowed to be used for production (Rijksoverheid, 2013B). However, it is not known whether duckweed is an accepted source, if not, this could limit duckweeds potential as biofuel in the Netherlands. Yet, currently duckweed is currently being used in biogas installations, indicating there are no major legal obstacles for using duckweed as source for biofuel.

Concluding, in regards to prevention and collection methods one must keep in mind the Flora and Fauna legislation comprised in the EU biodiversity strategy of 2020 (Hagen, 2015). The collection might, in fact, threaten fish populations in the waters, this is confirmed by Hoogheemraadschap De Stichtse Rijnlanden (2014), and could, thus, be a limiting factor.

6.1.2 Mode of governance
Following the classification of Driessen et al. (2012, p.145-146), a decentralized mode of governance can be identified. Duckweed is, indeed, removed by the water authorities, which is a form of decentralized governmental organization, as multiple water authorities exist in The Netherlands on regional levels (Maessen, 2014, p.21). The duckweed removal is, thus, based on local public governmental decision-making. An advantage of this type of governance is that there is high chance of stakeholder involvement. This characteristic is resembled in the problem at hand as, according to Maessen (2014, p.21), duckweed is only removed after receiving citizens' complaints. Hence, input of citizens is taken seriously. Moreover, policy officer water Arthur Hagen, is initiating a project regarding public participation concerning the duckweed removal. Yet so far, the mindset surrounding the duckweed is rather passive, and according to Hagen primarily focused on removal and preferably prevention (2015). Moreover the mindset seems to be pessimistic as according to Hoogheemraadschap De Stichtse Rijnlanden it is extremely costly and ineffective, indicating a preference for prevention (2014).

6.1.3 Sustainable development
For the past few hundred years the promethean view of humans overcoming all problems by technological innovation has been dominant and was rooted in modernity thinking, capitalism and the industrial revolution (Hopwood et al., 2015, p.38). The main focus was on economic growth as being central to human well-being. The growing environmental problems and the social problems linked with this gave rise to the concept of sustainable development, "meeting the needs of the present without compromising the ability of future generations to meet their needs" (WCED, 1978 in Hopwood et al., 2015, p.39). This report pointed out the importance of nature for human well-being and since then sustainable development has become increasingly important for governments all over the world. The Netherlands has to comply with EU environmental policy which has developed a long term strategy on social, economic and environmental aspects (Eur-lex, NN). This has forced the

Dutch government to broaden its mindset and to be open to innovative sustainable techniques. Therefore the government could be open to the application of duckweed to derive sustainable products.

6.2 Regime

The regime identified in this research is the status quo of duckweed: duckweed as waste. Currently, duckweed is removed from the urban waters after several complaints after which it is processed as waste (Riemer, 1994; Verma & Suthar, 2015). In this section the current regime is described based on its activities.

6.2.1 Stakeholders

According to Maessen the water authorities are involved in the removal of duckweed (2014). Their approach is passive: duckweed is only removed after complaints from citizens or when it is blocking pumping stations. One would think that to guard the water quality, duckweed would be removed in cases of eutrophication. Citizens, are another group of stakeholders. Urban citizens suffer from the stench of duckweed. As the unit of analysis of this research is urban water, only the urban citizens will be accounted for in this research. All in all, the municipality of The Hague, another stakeholder, gets around 12 complaints per year (Hagen, 2015). While it is the municipality that receives the complaints, the duckweed removal is the responsibility of the water board. Yet the municipality prefers the duckweed gone and mentions prevention as the most ideal option (Hagen, 2015).

Collection

The current regime of duckweed collection is simple. Duckweed is collected by the water authorities, or by firms contracted by the water authorities, when there is a need to collect it. Maessen has developed a flow diagram (Figure 6.1) based on current duckweed removal practices that can be used as a baseline for when duckweed is removed and what steps are best taken (Maessen, 2014, p.31). The basic practice is that when there are citizen complaints, action is taken quickly to remove the duckweed and stop the complaints. If there are more structural problems, for example with water quality, then more structural (mainly infrastructural) approaches are taken. Currently, there is no conformity what method is to be used to remove duckweed.

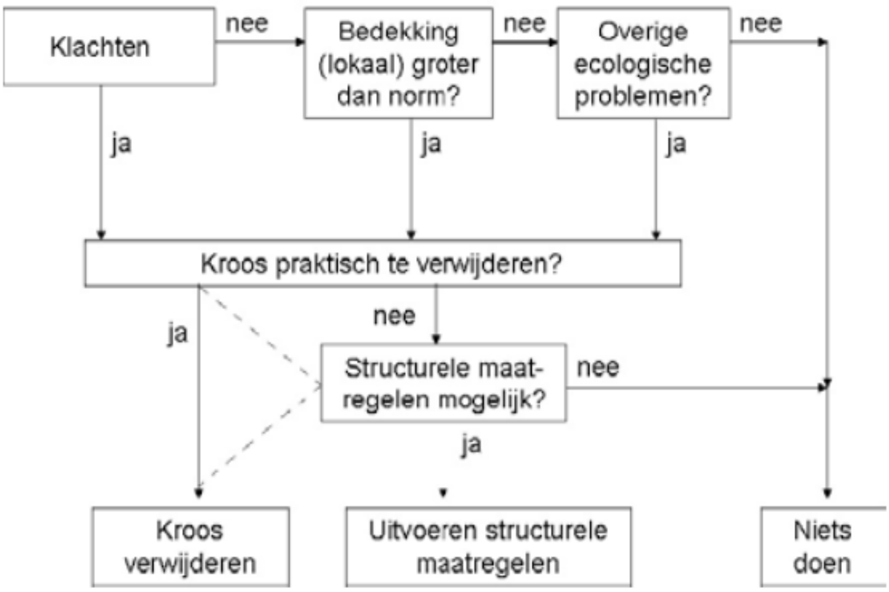

Figure 6.1. A flowchart what to do with duckweed (Maessen, 2014, p.31)

Water purification

Currently, two third of Dutch drinking water comes from groundwater (Water, 2008). Due to too much fertilization in agriculture, chemicals run off into the ground water. Yet the groundwater still has a relatively good quality, which allows for a simple filtering technique in the form of pumping up the water and adding oxygen. This cause the dirt to lump together and will be filtered out by sand, gravel or carbon filters. The rest of the drinking water comes from surface water stemming from the Rijn and the Maas. Unfortunately the dumping of chemicals harms the water quality in such a way that it needs to be cleaned thoroughly. The water can be pre-cleaned through filtration in the dunes, after this the same purification as of groundwater can be used. This can be seen in detail in figure 6.2. Surface water can also directly be filtered. However this is more complex as the water has to be disinfected with chemicals, heating and filtering. Next to drink water purification there is the purification of wastewater, which is done by the water boards (Rioned, 2009). Through the sewage water is transported to sewage water cleaning systems where the water is cleaned through the techniques described above. The Netherlands thus seems to have a well-organized water treatment system.

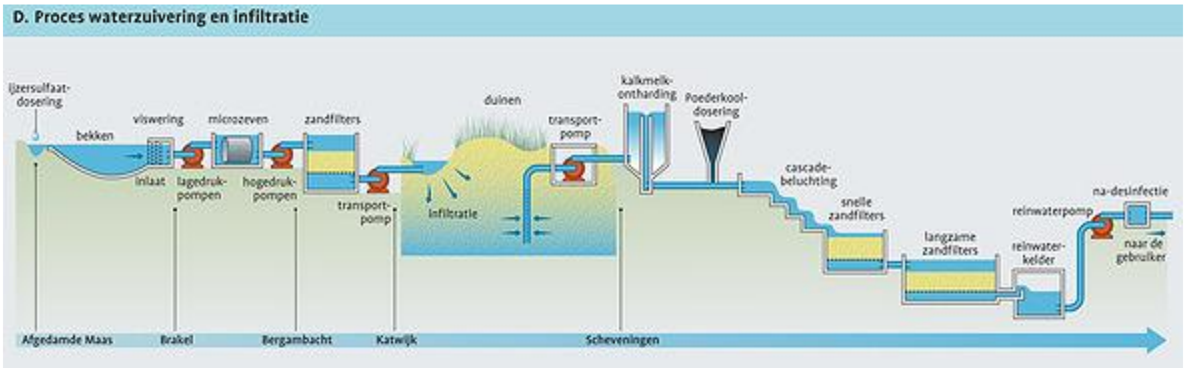

Figure 6.2. Water purification process (Kennislink, 2010).

Fertilizer companies

Currently, the Netherlands is a large exporter of agricultural products (NMI, NN, p.1) Its climate and fertile ground, together with ever increasing knowledge, technology and good organization of the whole sector, allowed the agricultural sector to expand. However, the downside of this expansion is increasing pressure on the environment due to a simultaneous increase of fertilizers and pesticides. Its consequences have led to a refocus on sustainable fertilizers. Additionally, the sector is starting to realize that the conventional fertilizers are non-renewable and therefore exhaustible. Next to this one must keep the current policies in mind. Due to European legislation on nitrate and Dutch legislation on water quality, the import for fertilizers is limited. The Netherlands also suffers from a manure fertilizer surplus and is obligated to minimize this surplus. Manure fertilizer would be a competition of duckweed and therefore limiting duckweed potential to transform from a niche to a regime. Adding to this competition of animal based fertilizers is the removal of the milk quota. This is expected to lead to more animal feces. Hence, more competition for duckweed fertilization possibilities. However, in line with the bio based economy, the nutrient cycle is being reduced. This could be beneficial to duckweeds' possibilities, but it could also promote the usage of animal based fertilizer. After all, as was shown in the product analysis, manure based fertilizer is more efficient than duckweed based fertilizer (Kostecka & Kaniuczac's, 2008). One of the currently biggest fertilizer producers is Yara which sells to 150 countries including The Netherlands. Yara is also influenced by the landscape of climate change and sustainable development and dedicated a CSR division to sustainable agriculture and fertilizers (Yara, 2012). Despite Yara's good intentions, it assumes no change in the type of fertilizer is needed when it is specifically applied with new techniques. Yara therefore does not mention the possibilities of bio-fertilizers. When big players like Yara, who have the power to lobby in favor of conventional fertilizers, are not supporting duckweed additional barriers are created for duckweed moving from a niche market to the regime (Kemp et al., 1998, p.180).

Energy companies

The Netherlands has a centralized energy system based on large energy production plants and a high-voltage grid for electricity transportation and a country-wide network of gas pipes. It is a privatized system where the government facilitates and steers, but also has committed itself to a transition to sustainable sources of energy. The main push towards sustainable forms of energy is identified in the Energieakkoord, an agreement the government concluded with companies and NGO's in The Netherlands (Sociaal-Economische Raad, 2013, p.67-78). This Energieakkoord thus indicates the direction the government, companies and civil society are trying to push the Netherlands. Because the incumbent energy regime is such an important part of today's societies (they are part of the infrastructure) it is difficult to actually reach radical changes in this system (Foxon, Hammond, & Pearson, 2010, p.1210; Kemp et al., 1998, p.177-179). There is, however, a tendency of the regime to move towards wind and solar energy, which it has already made part of its structure. However, the government does leave room for energy production from biomass. Currently, most biomass is used alongside fossil fuels in energy production. This biomass consists mainly of household waste, wood, and manure (Energieonderzoek Centrum Nederland, 2015, p.62-64).

The projections are also not very hopeful for the renewable energy sector as can be seen in figure 6.3, which also shows that the status quo is really fossil fuel based and invested. When looking at a list (which is incomplete because a large coal plant in the Eemshaven in Groningen is not on the list yet) of energy plants recently constructed in the Netherlands, it is clear that most investments have gone into coal and gas plants (Wikipedia, 2015). Thus there is a strong vested interest in keeping coal and gas in the Netherlands, because if these plants were to be closed their owners would suffer large losses (Kemp et al., 1998, p.179).

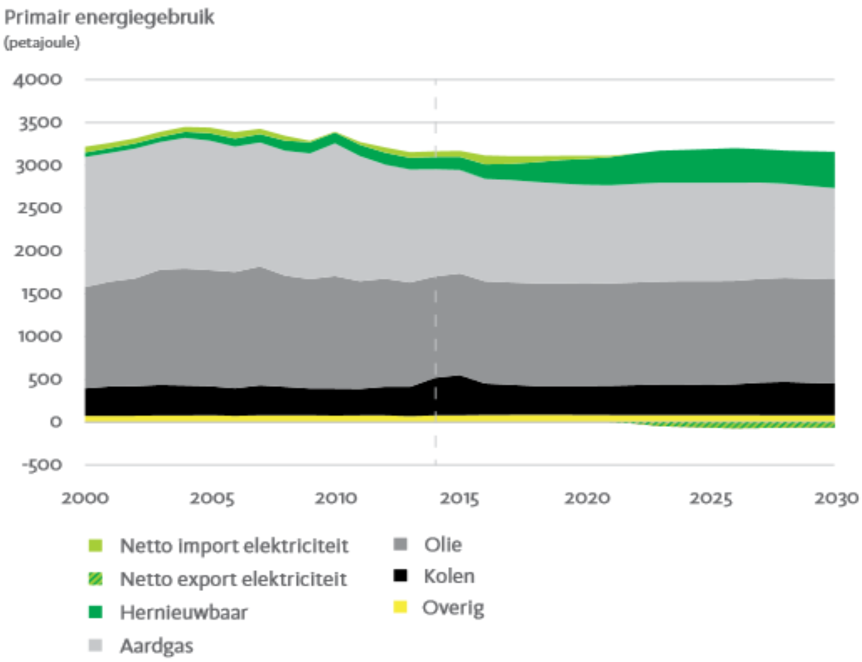

Figure 6.3: Primary Energy Use in the Netherlands per major energy resource group (Energieonderzoek Centrum Nederland, 2015, p.78)

Plastic producers
Currently, most plastic that is being used in the Netherlands is originated from fossil fuels. However, it is possible to make plastic out of biomass, such as mays, sugarcane and wood. Some bioplastics are biodegradable, some are not. but the market is growing rapidly (European Bioplastics, 2014). In the Netherlands, multiple research institutes and companies are working on and producing bioplastics. In the process, biomass is broken down into substances such as sugar or starch, which are then processed into bioplastics. Some of these created bioplastics are combined with fossil-fuel plastics. So far, duckweed has not yet been used to create bioplastics. The bioplastic market is very innovative, and new ideas and pilots are constantly being created. In October 2015, the first bioplastic was created from wastewater in the Netherlands while companies such as Avantium or BioHart, produce bioplastics based on biomass (STOWA, 2015).

Concluding, it can be argued that the regime duckweed is facing is mainly a technological regime (Kemp et al., 1998, p.182). Many different techniques are in place that block other techniques to move into the mainstream market. Not only because they are economically cheap and efficient in comparison with other techniques, but these techniques have also shaped contemporary society (Kemp et al., 1998, p.178). For instance, energy techniques that allowed a 24 hour reliable energy supply, car travelling and flying have become normal. A new energy source/ technique must thus also allow for this reliability. Moreover, in The Netherlands citizens are used to clean drinking water everywhere. If duckweed is to replace a current technique, it has to be cheaper and offer the same standards.

6.3 Niche
Even though the transition to a bio based economy might be about to reach the kick-off phase in the transition cycle, duckweed is still in its pre-development phase where just some pilot studies and experiments are being conducted

Water purification
The manure surplus stemming from agriculture does not just provide a barrier in the form of competition, but also an opportunity for the use of duckweed as water purifier. One of the problems of the manure surplus is the runoff into ground and surface waters, which leads to large amounts of phosphorus and nitrogen accumulating in the waters (Rijksoverheid, 2015C). Both chemicals are dangerous to human health and should therefore be limited. As described in the product analysis part, duckweed is capable to remove those chemicals from the water (Niewenhuis & Maring, 2009,p.32). This provides a viable possibility for duckweed to move from a niche into the regime. However, current purification methods for drinking water stemming from surface water are simple and might therefore not need duckweed (Water, 2008). Additionally, to convert surface water to drinking water more complex techniques are needed and duckweed is not sufficient enough. Hence, the solid organized water treatment system in the Netherlands can be seen as a barrier to the application of duckweed as water purifier. Another obstacle to the use of duckweed as water purifier is that it could conflict with WB21 and Natura 2000 as it is a monoculture and thereby a threat to biodiversity (Hagen, 2015). Yet it could play a role as pretreatment in waterways were duckweed naturally grows. This would reduce the intensity of later on cleaning.

Fertilizers
While there is a demand for organic fertilizer due to the depletion of chemical fertilizers, the mainstreaming of duckweed as fertilizer suffers from some barriers as the competition with the more efficient manure based fertilizer and the abolishing of the milk quota in the EU (NMI,NN). Yet, duckweed still has the potential to become a mainstream fertilizer. According to Dutch government manure fertilizer can only be used to a limit as it is dangerous to human health (Rijksoverheid, 2015B). The manure surplus thus only provides a limited competition to duckweed because the manure surpluses cannot be used as fertilizer. When the manure fertilizer has reached its allowable limit, a shift to other organic waste is needed. This could become duckweed's window of opportunity. Additionally because duckweed is odorless, this benefit could be used in more densely populated areas.

Biofuels
The Dutch natural gas production will decline both because the gas fields are getting empty, but also because of social factors such as the earthquakes in Groningen. The Netherlands will as a consequence most likely import more gas from foreign partners (Energieonderzoek Centrum Nederland, 2015, p.143-144). One of these is Russia, however, with ongoing tensions between Russia and the West, politicians have mentioned frequently that they do not desire to become dependent Russian gas. Because duckweed can be turned into gas (or used to enhance gas production of anaerobic digestion processes), is available in the Netherlands, and fits to a large extent in the current infrastructure, it could reduce dependency on Russian gas and replace part of the dwindling natural gas production (Kemp et al., 1998, p.177). These types of gas are called green-gas. It is expected that the Netherlands will develop towards this green-gas state, if the market prices do not change dramatically (Energieonderzoek Centrum Nederland, 2015, p.132). This is even more logical when it is realized that green-gas is carbon neutral and does not emit extra greenhouse gasses into the atmosphere than it absorbed when the biomass was alive. Similar expectations exist for bio-oil (ethanol) and bio-plastics (Energieonderzoek Centrum Nederland, 2015, p.8-79). Furthermore, to reach the climate goals in 2050, it is expected that a lot of biomass needs to be important for bioenergy purposes (Energieonderzoek Centrum Nederland, 2015, p.204-205). If duckweed were used, these imports could be reduced. Thus there are ample opportunities for duckweed fuels.

However, one of the main obstacles for biomass-energy is the uncertainty that enough biomass can be structurally and timely delivered to the power plants for a long period of time (Ibid., p.222). Moreover, duckweed does not grow well in Dutch winter periods. Therefore, it is difficult to have a stable flow of duckweed into the production system during winter. That is a barrier for its use, because either duckweed must be stored as reserves to be used during winter, or other biomass products must be used during winter. Another problem is that there has been little to no experience with (large-scale) fermentation, gasification, liquefaction, pyrolysis, or other methods, of duckweed, mainly because it turned out to be difficult to compete with fossil fuels and to develop good business cases (Energieonderzoek Centrum Nederland, 2015, p.219-222).

One practical example that is currently being undertaken in The Netherlands is that Rotie, a company that collects organic waste and turns it into biogas or biofuel. They are going to test whether duckweed is a possible organic waste product that they can use in their production process (Rotie, 2015). The firm Indaver indicated that duckweed indeed has potential to be used, but it all depends on the costs of the duckweed in the gas production process (Indaver, 2015). Unfortunately, in The Netherlands duckweed has not been tested on a large-scale yet. As a consequence, their benefits and costs are also more uncertain, thus taking the step to trust the new technology is more difficult (Kemp et al., 1998, p.177-179).

Collection

As shown in chapter 4 a number of collection methods have been developed by various actors that are capable of removing duckweed from waterbodies. Some of these firms are hired to remove the duckweed, while others try to sell their duckweed machines to actors that remove duckweed such as water boards or actors with controlled duckweed basins (Maessen, 2014). However, when collecting the duckweed from public waterways, these collection practices must be able to collect just the duckweed and leave all other parts of the waterways alone. Unless, of course, the duckweed collection machines can also at the same time collect and separate floating waste with the duckweed, because that would be an added bonus to the collection process. Should such a collection method be developed, the added value for water boards will increase substantially. The municipalities are open for innovation which would allow a new collection method to transform into a regime (Hagen, 2015). The biggest barrier will probably be the budget as the collection methods differ largely in initial costs and maintenance costs (Maessen, 2014).Right now, the niche is still quite empty with few activities going on in public waterways. There are, however, possibly large opportunities for duckweed collection by water boards or private firms because of the increasing recognition that duckweed can be an valuable organism that can be turned into a wide-variety of products. That recognition will increase demand for duckweed, which right now is still non-existing, and thus increase the possibilities to collect and use duckweed from public waterways because more money will become available to be allowed to use the duckweed, hence covering any associated costs the water board might have.

Bioplastics

Because plastic is made from, fossil fuels, there is a growing demand for bioplastics (European Bioplastics, 2014). However, so far, biomass from duckweed is still research in progress. There are no known companies or institutions that are capable of turning duckweed effectively and profitably into bioplastics. Especially the impurity of the duckweed from public waterways and the possible pollutants that it has taken up can be troublesome when it is to be turned into duckweed, both for health as for production reasons (Zeller, Hunt, & Sharma, 2013, 381-385). However, with the continuing interest and research into duckweed, it is possible that scientists will find ways to use duckweed effectively for bioplastics. Moreover, with the growing demand for bioplastics, the demand for its resources will increase as well. Unlike important types of biomass such as wood or corn and sugarcane, which are also demanded for other products such as food, buildings, furniture, and energy, duckweed is still a product that is open to utilization by humans. Thus, while demand for the current types of biomass will likely increase, also because of population growth, duckweed is still unexploited and can fill that gap. Therefore, duckweed has a lot of potential as a resource for bioplastics, but that potential is currently not yet realized.

7. Discussion - Management advice and Transition pathways

The analysis carried out in the above chapters yielded several results regarding ecological information, prevention methods, collection techniques, products descriptions and market possibilities of duckweed in urban water systems in The Netherlands. Given these results several discussion points will be discussed in order to provide an answer to the research question and a management advice.

Firstly, some general remarks regarding the research. The methodology mainly consisted of a literature research which was complemented with several interviews with experts. Consequently, the report stays rather theoretical and is highly dependent on the quality of the studies used as reference. Additionally, the application to reality is not entirely known. Furthermore, due to time constraints, not all products could be concluded in the analysis and a pre-selection had to be made. More time would have allowed more in-depth research. Next to this, the initial question posed by KWR was rather technical. While this is a transdisciplinary study, technical experts were missing, leading to superficial technical analyses. If KWR indeed requires more insight in technological aspects, future research with technological experienced researchers is needed. One last general remark is the focus on the Netherlands in general. Due to practical information availability and time constraints, it was not possible to focus on a specific Dutch area. The conclusions could thus differ for specific areas and therefore the results of this research cannot be generalized to other areas.

Secondly, as mentioned above, duckweed composition is highly dependent on the contamination of the water basin in which it grows. Water quality is a fundamental piece of knowledge to fully understand the potential of duckweed and its possible application as a product. Giving the time frame allowed for this research, such kind of testing was not feasible. Thus, future research should address the specific composition of duckweed species present in a particular research area.

Thirdly, the most suitable prevention method is not clear cut and depends on characteristics of the waterway such as depth, nutrient concentration, flow velocity, dead ends, and its shape. Many options have been presented that can help reduce or prevent duckweed growth and should be taken into consideration for implementation. However, future research is needed to determine how the implementation can be done most effectively and to highlight waterways for which prevention might be the most suitable option. This analysis should consider elements of technical feasibility, but also integrate social norms and acceptability considerations.

Fourthly, regarding collection methods similar conclusions as for prevention techniques can be drawn. Implementation of these practices depend on several parameters, namely duckweed coverage, reachability, morphology, water depth and waterways surroundings. Thus, it is recommended to research these elements to assess which methods might be more successful for urban water basins. Further, we found that transport means have not yet been investigated in depth. We believe this element should be central to the determination of whether duckweed should be collected and processed or prevented. This is due to the fact that trucks are the vehicles mostly used for transport and the use of such means might have a greater impact on GHG emissions and the environment rather than preventing the growth altogether.

Fifthly, the current mode of governance might hinder the transition of duckweed products from a niche to a regime market. To date, the only institutions involved in the management of duckweed are regional water authorities. The involvement of other actors, for example from the private sector, might enhance the chances of achieving the above mentioned transition and render the management of the duckweed resource more successfully. It is therefore suggested to take into consideration the possibility to embark on a partnership with the private sector. Particularly, two companies were found in the energy sector, Rotie and Indaver, who might be interested in processing the duckweed recovered from urban waterways to produce biogas.

Finally, for all possibilities presented in the above chapters, we suggest the client to undergo an impact assessment and cost benefit analysis in order to determine not only the most economically feasible scenario, but also to understand the natural and social impact of specific methods. Considering that DWA is a public governmental body and their final goals do not correspond with increasing their income, but providing a service to the community, and that KWR as a consulting body should align with the objectives of DWA, we recommend that the latter two elements of natural and social impact assume a central role in the determination of the scenario to be implemented. Figure 7.1 summarizes possible scenarios that might result from prevention, collection and processing of duckweed. Boxes in green indicate the recommended options based on urban water systems.

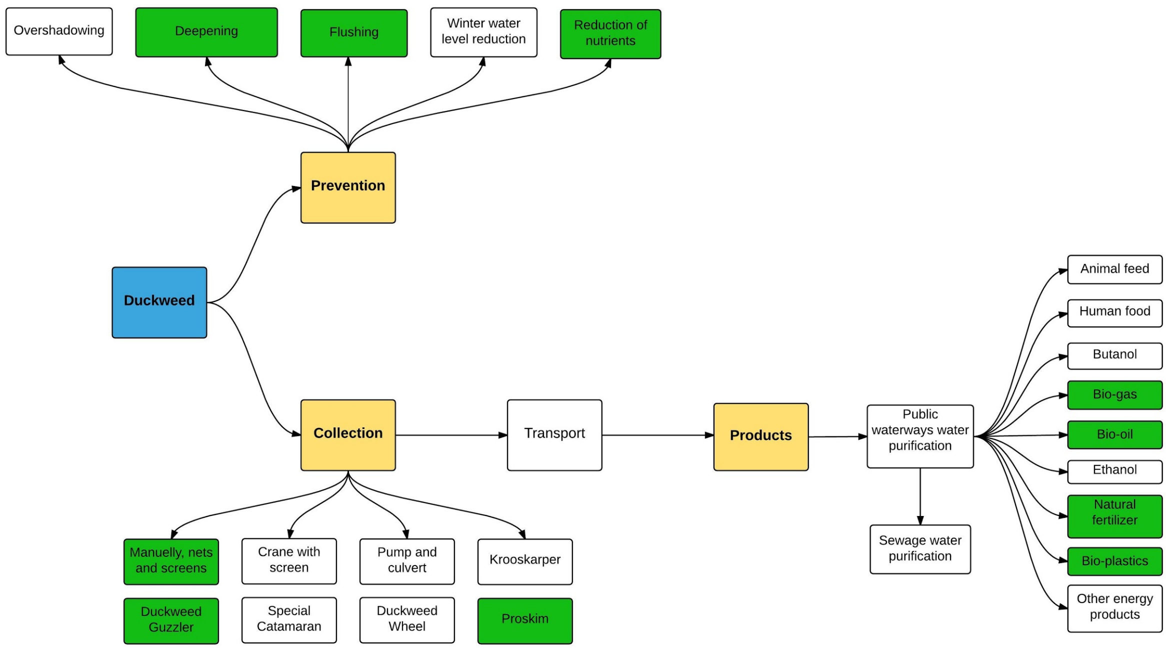

Fig 7.1. Flow diagram with the possibilities of duckweed. Larger version can be found in Appendix I

8. Conclusion

This research set out to answer the following research question:

In what way can prevention, collection, and processing methods of duckweed in the urban water systems of The Netherlands be managed to foster a transition from undesired waste to a useful sustainable product?

After providing general background information on the ecology of duckweed prevention, collection, transportation methods and possible duckweed products were identified. The contamination level of the water and hence the duckweed proved to be important. On the one hand via eutrophication it stimulates duckweed growth and thus the negative side effects as stench and hypoxia. On the other hand the stimulation of duckweed growth opens possibilities for duckweed based products of which the level of contamination determines the possibilities. Another reason to keep contamination in mind, is that urban areas, such as the Delfland area, water bodies are often contaminated. A logical conclusion therefore would be to prevent duckweed growth, which is the current municipal policy. Lowering the nutrient level by dredging would be the most suitable option to prevent duckweed. Yet as showed above, there are several interesting options to use duckweed. Table 4.4 gives an overview of possible collection methods and when these are most suitable. Manual techniques cost little and score relatively high in efficiency. However, on the long term the Proskim water skimmer and Duckweed guzzler would be more profitable despite their high initial costs. These methods are more efficient, cover a larger scale and facilitate transport. Flow-chart 7.1 shows the most promising duckweed products (depicted in green.) Due to strict food safety regulations, food and feed options are not possible. Mildly contaminated duckweed could be used as fertilizer once the limit for manure use is reached.

While duckweed is slightly less effective as manure composting, duckweed does provide an odorless option. Finally, duckweed can always be used as ingredient for bio-energy or bioplastics as the level of contamination for these applications is not important. Hence, and contaminated duckweed could be used. Bio-plastics offers an alternative to bio-plastics from sugar cane which can be used for other product. Duckweed Bio-energy is thus the most interesting option. However, duckweeds reliability as an energy source must be tested. Additionally, turning duckweed into energy or plastics is less valuable than turning it into human food for example, as the energy is burned and lost. Therefore, the choice regarding the type of potential product does not only depend on technical aspects, but on economic and social ones as well. Moreover, duckweed does not enter into a vacuum market, but has to find a way into the existing market.

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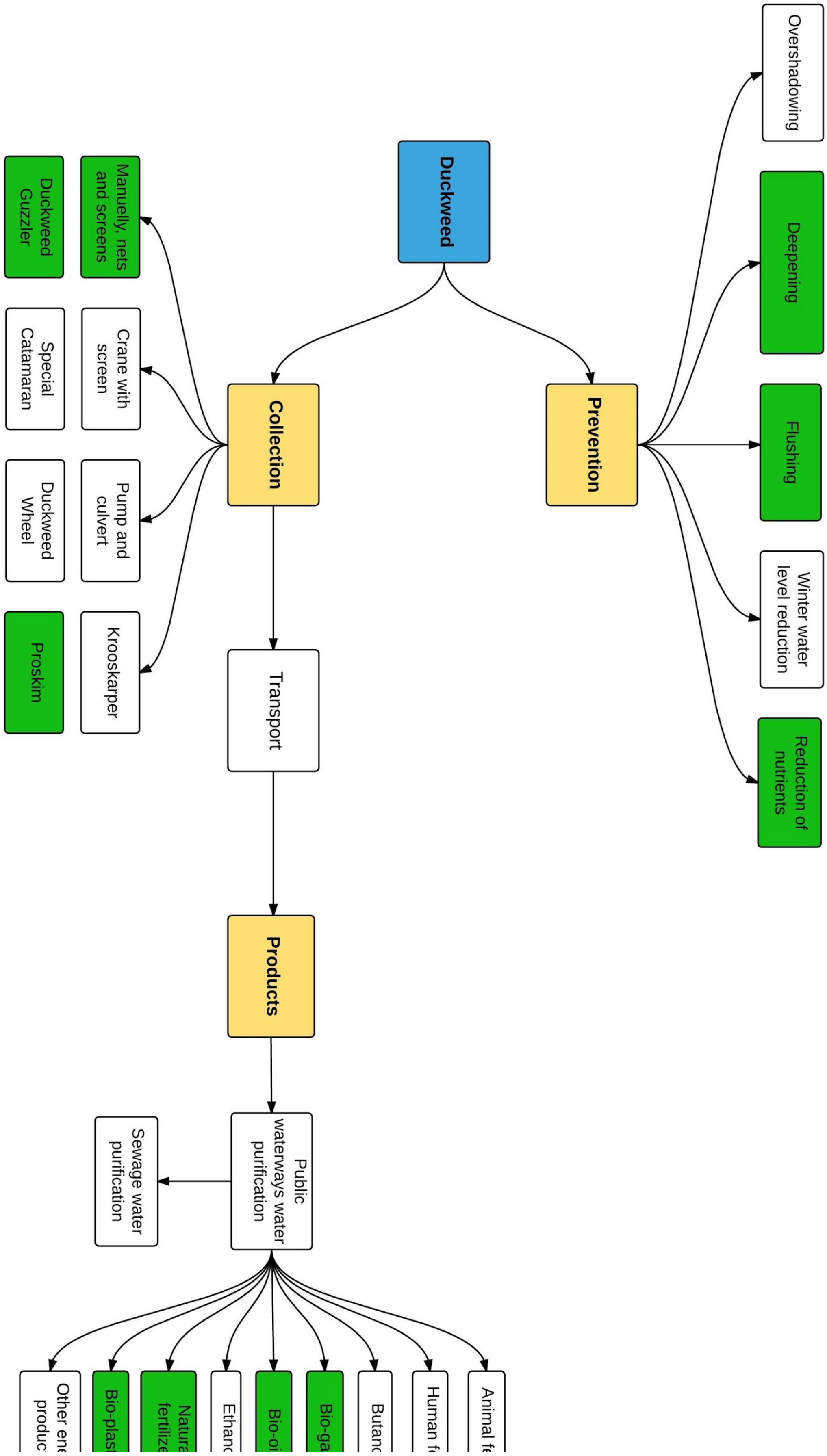
APPENDIX I: Flowchart



APPENDIX II: Contact information

Type of organization	Organisation Name	Contact person	Contact information
Biogas company	Rotie	Mike Tiggeler	mike.tiggeler@rotie.nl
Biogas company	Indaver	Robert Jansen	Robert.Jansen@indaver.nl
Green maintenance	Haeghe Group: duckweed collectors in the Hague	Robert Molenkamp Robert den Oude Daphne van Gent Rob Snijders	R.Molenkamp@haeghegroep.nl, R.denOude@haeghegroep.nl, D.vanGent@haeghegroep.nl, R.Snijders@haeghegroep.nl
Water Governance The Hague municipality	The Hague municipality	Arthur Hagen	arthur.hagen@denhaag.nl
Duckweed farmer	GreenSun Produc	Tamra Fakhoorian	tamraf9@gmail.com