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MICROALGAE – ENERGY PRODUCTION AND WASTEWATER PURIFICATION

Three Scenarios for Microalgae Cultivation in the Kujala Waste Management Center

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JÄRVELIN, KARI, PEKKA:

Mikrolevät – Energian tuotto ja jätevesien puhdistus
Kolme skenaariota mikroleväkasvatukselle Kujalan jätekeskuksessa

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TIIVISTELMÄ

Vähenevät fossiiliset polttoainevarat ja niiden saastuttavuus ovat lisänneet panostusta kehittää kestävämpiä ja hiilineutraaleja energian lähteitä. Mikrolevät ovat lupaava raaka-aine uusiutuville energialähteille, kuten biodieselille ja biokaasulle. Verrattaessa nykyiseen ruokakasvipohjaiseen biopolttoaineen tuotantoon mikrolevät kasvavat nopeasti, eivät vaadi viljelyskelpoista maata ja niitä voidaan kasvattaa ravinteikkaissa jätevesissä. Mikrolevien biopolttoaineen tuotto per hehtaaria kohti vuodessa on monin kerroin suurempi kuin muilla biopolttoaineilla.

Tämä opinnäytetyö on osa ALDIGA (Algae from Wastewater for Combined Biodiesel and Biogas Production) -projektia, joka kehittää konseptia mikroleväpohjaiselle biopolttoainetuotannolle suljetussa kierrossa. Päätarkoituksena on saada mikroleväkasvatusprosessi mahdollisimman ekotehokkaaksi ja taloudelliseksi. Pääosapuolet projektissa ovat Valtion teknillinen tutkimuslaitos (VTT) hallinnoijana, Helsingin yliopisto (Lahti), Lahden ammattikorkeakoulu (LAMK), Hämeen ammattikorkeakoulu (HAMK) ja Suomen ympäristökeskus (SYKE). Projektia rahoittaa Teknologian ja innovaatioiden kehittämiskeskus (TEKES).

Kujalan jätekeskuksessa sijaitseva Kujalan Komposti Oy on toteuttamassa biohajoavan jätteen käsittelyn kehittämistä, josta on menossa ympäristövaikutusten arviointi (YVA). Suunnitelmat sisältävät biokaasu- ja mikroleväkasvatuslaitoksen rakentamisen. ALDIGA tutkii mikrolevän kasvatusmahdollisuuksia Kujalan Komposti Oy:n jätevesissä. Tämä opinnäytetyö pyrki määrittämään Kujalan jätekeskuksen potentiaalin leväkasvatukselle kolmen skenaarion avulla. Worst-case, Moderate, Optimal skenaariot mallinsivat biomassan tuotantoa, tilavaatimusta ja vedenkulutusta kolmissa eri olosuhteissa. Tämä antoi ymmärrystä Kujalan alueen minimi- ja maksimikapasiteetista.

Tulokset osoittavat, että Kujalan alueella mikrolevätbiomassan tuotto on minimissään 40 t/a ja maksimissaan 1000 t/a. Veden kulutus näillä tuottotahdeilla olisi 14700 - 44100 m^3/a raakaa jätevettä.

Avainsanat: mikrolevät, biomassan tuotanto, tilavaatimus, veden kulutus

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JÄRVELIN, PEKKA, KARI:

Microalgae – Energy Production and Wastewater Purification
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ABSTRACT

The diminishing fossil fuels and the emission problems are increasing the effort to develop more sustainable and carbon-neutral energy resources. Microalgae are a promising resource of renewable energy such as biodiesel and biogas. Compared to the current biofuel production from food crops, microalgae grow fast, do not require arable land and can be cultivated in nutrient rich waste waters. The biofuel productivity of microalgae per hectare per year is many times higher than with other biofuel resources.

This study is a part of the ALDIGA project (Algae from Wastewater for Combined Biodiesel and Biogas Production), which is developing a concept for closed circulation production of algae-based biofuel. The main focus is to make the process eco-efficient and cost-effective. The project participants are the Technical Research Center of Finland (VTT) as a leading partner, University of Helsinki (UH) (Lahti), Lahti University of Applied Sciences (LAMK), Häme University of Applied Sciences (HAMK) and Finland's Environmental Administration (SYKE). The project is funded by the Finnish Funding Agency for Technology and Innovation (TEKES).

Kujalan Komposti Oy, located in The Kujala Waste Management Center, is improving the level of its organic waste management and is currently undergoing an environmental impact assessment (EIA). This includes the designing of a biogas plant and a microalgae cultivation facility. ALDIGA is studying microalgae cultivation in the Kujala area's wastewaters. This thesis strived to define the potential of microalgae cultivation in the Kujala area through three scenarios. Worst-case, Moderate and Optimal scenarios modeled the biomass productivity, area requirement and water requirement parameters in three different situations. This gave a range and understanding of the minimum and maximum capacity the Kujala area has.

The results indicate that Kujala has a minimum of 40 tons per year and maximum of 1000 tons per year microalgae biomass productivity in its area. Water consumption for this is 14,700 - 44,100 cubic meters per year of raw waste water.

Key words: microalgae, biomass productivity, area requirement, water consumption

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- my life companion Jenny

This thesis is dedicated to my mother, who wrote her Master’s Thesis with a portable typewriter without word processing programs or internet.

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1 INTRODUCTION

Fossil fuels, such as crude oil, coal and natural gas, are among the most important energy resources in the present economies. Crude oil for example is used diversely in industry and transportation all around the world. Crude oil and other fossil fuels are, however, a strong source of carbon dioxide (later referred to as CO_2) and their natural reserves are diminishing fast and coming more and more expensive to utilize. The global awareness of this matter and the concern of environmentally friendly solutions, have increased the role of renewable energy resources. New legislations, emerging markets and funding in research are building a way for biomass-derived fuels such as bioethanol, biodiesel and biogas. These biofuels have a crucial role in finding a replacement for diminishing fossil fuels. (Chisti 2007; Shen et al. 2009)

The most widely used biofuels have been food crop-based solutions. These first generation biofuels made out of corn, soy bean or palm oil are debatable and meet a lot of criticism for affecting negatively on the food production and price. The focus of research have turned more to second generation biofuels which are based on more sustainable production methods. Microalgae are considered to be the only efficient and sustainable resource to meet the demand of transport and industry fuels (Chisti 2007). Microalgae have many positive features that make them superior compared to other biofuel resources. Lots of research is nevertheless done to overcome some key problems in commercial cultivation and utilization.

This Bachelor's thesis is a part of a Finnish project called ALDIGA (Algae from Waste for Combined Biodiesel and Biogas Production), which was started in the year 2010. ALDIGA studies eco-efficient biofuel production based on wastewater grown microalgae. The project strives to form a cost-effective microalgae biofuel production concept for Finnish circumstances. The idea is to use closed circulations and to utilize side streams such as waste water and CO_2 emitting sources. This way the need of primary energy will be reduced and waste will be reutilized as a feedstock. ALDIGA participants are Technical Research Center of Finland (VTT) as a leading partner, University of Helsinki (UH) (Lahti), Lahti University of Applied Sciences (LAMK) and Häme University of Applied Sciences

(HAMK), Finland’s Environmental Administration (SYKE) and many companies for example the Kujalan Komposti Oy. The project is funded by Finnish Funding Agency for Technology and Innovation (TEKES) and done in co-operation with foreign institutions and universities (Kostia 2011).

Kujalan Komposti Oy (later referred to as Kujala Oy) is planning to improve the level of its organic waste management by building new processes such as a digestion plant (Kujalan Komposti Oy 2011). ALDIGA is studying the possibility to grow microalgae in closed circulation with Kujala Oy’s other processes. The aim of this thesis is to model microalgae biomass production, area requirement and water consumption in the Kujala Waste Management Center (later referred to as the Kujala Center. This is done with three scenarios which will give a range and understanding of the Kujala Center’s capacity and potential at its worst and best.

This thesis is based on peer reviewed literature and the information provided by ALDIGA and Kujala Oy staff. In addition, the suitability of a SuperPro Designer software program to the modeling of the scenarios was tested.

2 MICROALGAE’S VERSATILE FEATURES

Alga is a broad definition for a group of eukaryotic or prokaryotic water organism ranging from seaweeds to microscopic unicellular organisms (Mata et al. 2009, Oilgae 2011a). This study concentrates on the micro-level algae, especially unicellular green microalgae. The majority of these are microscopic photosynthesizing (autotrophic) organisms that live in saline and fresh water around the world. They have the same qualities as plants except that they have no roots or leaves. In order to grow properly, microalgae require light, a carbon source and nutrients such as nitrogen and phosphorus. Other factors that affect microalgae growth are temperature, pH and existing bacteria (Chisti 2009). Autotrophic microalgae live and grow with sunlight energy, carbon dioxide and water. Some microalgae are heterotrophic and they cannot utilize the energy from the sun. They take energy and carbon source from organic compounds existing in the water. Some strains are able to use both metabolic routes according to the situation. These strains use sunlight when possible and organic compounds in circumstances without light.

Microalgae, as a resource of biofuels, have been studied for approximately 50 years (Chisti 2007) but the global interest started in the 21st century. Microalgae are studied because of their lipid content, fast growth rate and minor or environment impacts. Biofuels are produced from the lipids that crops or microalgae contain. Compared to food crops, microalgae grow many times faster, do not require as much water or nutrients and they contain the highest amount of lipids per dry weight. Some microalgae strains have up to 70 per cent lipid content per dry weight and have 16 times higher oil yield per area compared to conventional lipid resources (Mata et al. 2009; Oilgae 2011b). Microalgae do not require arable land or fresh water to grow so the cultivation does not disturb food production. Mixotrophy allows the possibility to grow in different environments and to adapt to changing conditions.

Microalgae are suitable for efficient and meaningful biofuel production. Microalgae can be grown in wastewaters; they purify the water by using the nitrogen and phosphorus (Aslan et al. 2006; Ruiz-Marin et al. 2009). Also, when CO_2 and heat are taken as an excess side output from different activities, the net energy required to the cultivation drops low. The efficiency of the system is increased when microalgae biomass is utilized further as biogas and residual as compost after lipid extraction. Other high value products, for example for chemical industry, can also be produced from microalgae.

Suitable strains and cultivation conditions can also be obtained in northern latitudes. Widely studied strains are for example *Chlorella protothecoides, Chlorella pyrenoidosa and Botryococcus braunii.* These strains also live in Finnish waters. They have a high lipid content and they are capable of mixotrophia, which is useful at higher latitudes where light is not abundant.

Microalgae can be cultivated in many ways in open or closed cultivation. Open pond is the simplest and most affordable solution. It requires only a few components and moderate capital. Compared to closed systems, such as bioreactors, open ponds have nevertheless lower yield and they are more vulnerable to contamination. Bioreactors have better microalgae productivity but require more space and expensive and complex process systems (Ugwu et al. 2007).

3 KNOWLEDGE GATHERING & WORK PROGRESSION

A great amount of background work was done for this study. In order to understand the main objective and to screen it properly, multiple and indefinite resources had to be managed and clarified. Co-operation was done with many people and teams related to this subject. Chronologically the work proceeded through five main stages: Understanding the subject, Gathering information, Constructing the data, Co-operation and Screening the scope of the work. Repetition of these stages increased the knowledge and understanding as the work progressed. Figure 1 describes how the work progressed and different partners helped and guided the work.

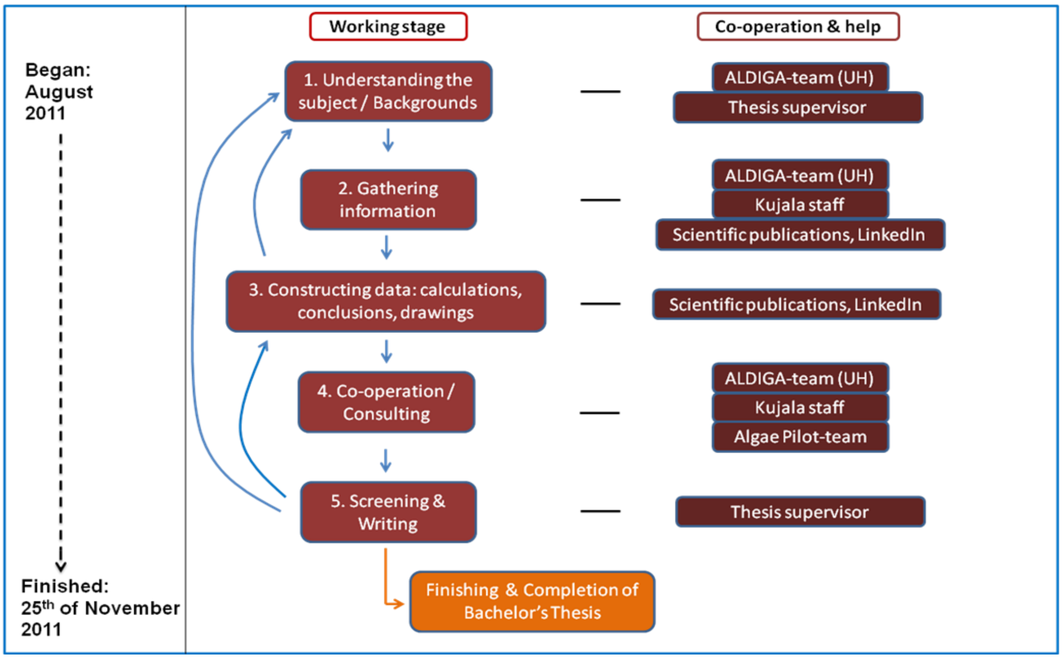


Figure 1. A sketch of the chronological working progression and knowledge gathering

The work was started at the beginning of August with the help of the thesis supervisor Silja Kostia and the ALDIGA research team from University of Helsinki (UH). The main parameters and concepts were discussed, which gave background information to the focus and objective of the work. In the second stage more specific information and research results were gathered from scientific articles and other published and peer reviewed data. This data was analyzed and constructed in stage three and consulted with others in stage four. The ALDIGA research team, Kujala Oy’s staff and Microalgae pilot unit team gave valuable information to questions and problematic situations. In the fifth stage, the aim and direction was specified. In addition to the chronological progression, the work also went back and forth between different stages and partners, to clarify and solve numerous complexities. The five stage loop was repeated several times during three months of the four month study period. This also refined the idea and the aim of the three scenarios. The last month was more concentrated on writing the actual work to form a functional entity.

3.1 Microalgae pilot unit

“Microalgae pilot unit” is a project that is planning and building a pilot-scale microalgae cultivation system. The scale-up of different biochemical processes from laboratory level research to commercial industrial production requires practical testing. Detailed and complex processes are often very situation specific and are sensitive for alteration. Pilot is an interphase between laboratory and commercial scale to test and further study how results and requirements change with increased quantity and size. ALDIGA research team (UH) is part of the pilot unit with other participators from Lahti Science and Business Park and Aalto University. The objective is to build a functional cultivation reactor of approximately 100 liter to test the results gained in laboratory (ALDIGA 2011b).

3.2 LinkedIn

LinkedIn is a social network site for global business related communication and interaction. The site offers a possibility to gain visibility in one’s own field, find job offers, discuss and ask from other professionals anything related to one’s field. LinkedIn was used in this thesis as a source of information and to compare data found elsewhere on microalgae. This was done by registering as a member to a group called Algae to Growdiesel and interacting online with others (LinkedIn 2011).

3.3 SuperPro Designer

Modeling of complex and large processes can be unnecessarily time-consuming and difficult without a proper modeling tool. Intelligen Incorporation’s modeling software program SuperPro Designer (later referred to as SPD) was tested in this study. With this program one can build, model and calculate different kinds of processes and manage broad entireties and situations. SPD is designed especially for process development and engineering in biotechnology, water purification and pharmaceuticals to name a few (Intelligen Inc. 2011).

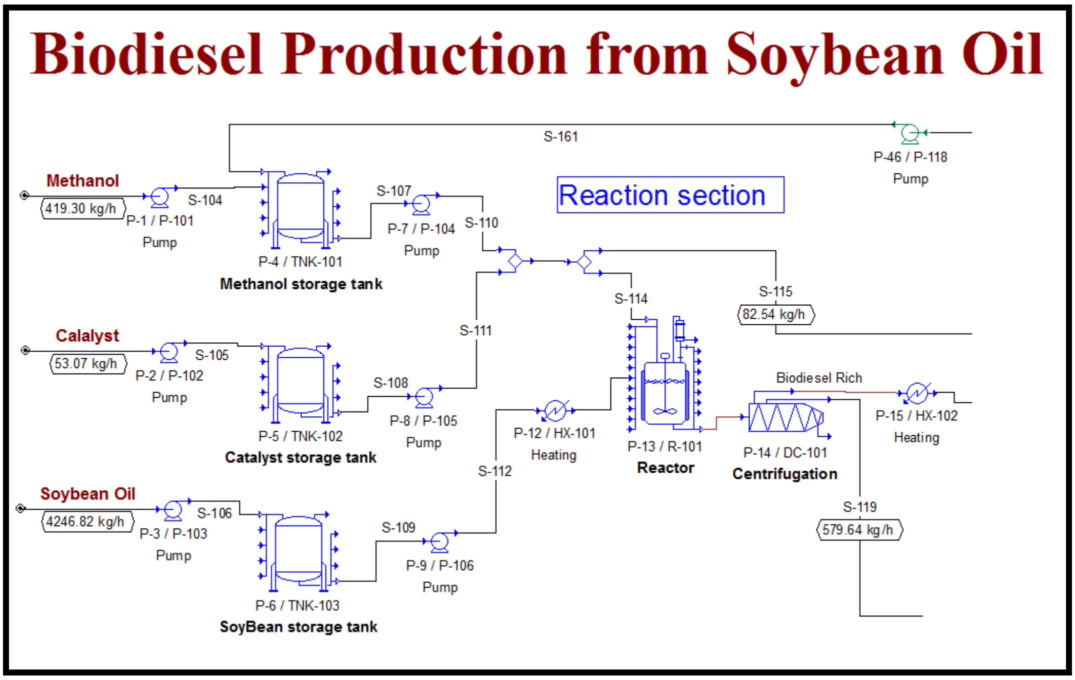


Figure 2. An example of biodiesel production modeling with SPD (screen shot, modified from SPD database examples)

Even though microalgae cultivation is a rather simple sum of certain parameters, the biochemical process on a molecular level is a complex entirety and the modeling of it requires a proper tool. SPD’s suitability to model microalgae cultivation processes was studied. Microalgae cultivation research articles with SPD modeling was searched and co-operation was done with Heli Hiltunen, a student at HAMK. Hiltunen is part of the ALDIGA project and she studied SPD’s suitability for the biogas plant modeling. The program was studied through tutorial and software examples. The actual modeling work was left out of this study as the thesis comprises only certain parameters which are easy enough to handle without a professional modeling tool.

3.3.1 Learning progress

The SPD program was purchased for the project in the beginning of August but a long period of time was consumed before the software worked properly. Many problems with the work computer and setup of the software occurred and delayed the use of the program approximately by a month.

The studying of SPD was started by getting familiar with the program and its functions. A large manual included with the program gave specific information on every function of SPD. As the detailed manual proved to be too difficult for an initial approach, a tutorial of the program was used to learn the first steps and phases. Figure 3 shows the overall view of the tutorial modeling.

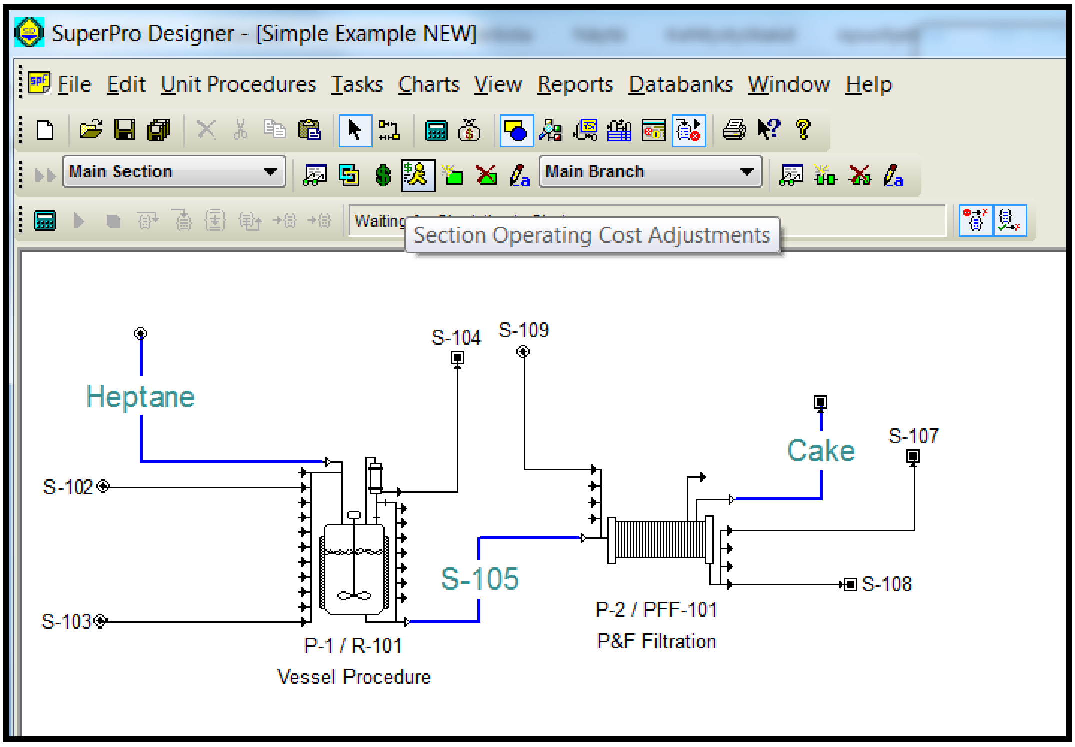


Figure 3. Tutorial modeling. Simple example of constructing the streams and processes to work accurately (screen shot, modified from SPD program 2011)

The tutorial modeling teaches the main functions and the construction of a basic process model. It teaches how imaginative reactants A and B react with heptane in stoichiometric process and produce end product C and side products. The rather simple modeling picture includes detailed information on the character of reactants and products. One can say that SPD is not able to ‘guess anything’. This means that every parameter and required data must be applied before the program can run any simulation. This was noticed already during the tutorial practice as one missing detail gave an error message and stopped simulations. Solving the missing data, proved to be difficult and time consuming.

Professional help was needed after personal familiarization with the program. Eemeli Hytönen from VTT’s side in ALDIGA instructed and gave support in the learning progress. He also helped to understand the potential of the program and the objective of the usage. Hytönen has experience in modeling and process simulation albeit not specifically in the SPD. His help was important nonetheless. Heli Hiltunen had studied SPD in Canada as an exchange student and gave support on the problems faced with the SPD. Interaction was held in September and October via emails and one Skype call.

The basic idea and functions of SPD was learnt during the thesis work. SPD is designed to be user friendly and quickly adaptable but a certain amount of intensive learning and testing is nonetheless needed. Hytönen’s and Hiltunen’s assistance was valuable but an instructed studying course is necessary to learn to use the program properly. Based on the experience gained during this thesis work SPD is potential software for microalgae cultivation modeling. However, the modeling should be used to a complex and a complete process in order to get the benefit from the software. As this thesis concerns microalgae cultivation on a more simple level, the utilization of SPD in ALDIGA project is postponed.

4 KUJALA WASTE MANAGEMENT CENTER

4.1 Area and processes

The Kujala Center is a waste sorting and treatment center located in Lahti. It is maintained by the Päijät-Häme Waste Management Company (later referred to as PHJ) and it has modern waste utilization and sorting facilities for example for biowaste, house hold waste, liquid and slurry waste. It also handles paper, glass and metal and has processes for contaminated soil remediation and energy waste crushing. The Kujala Center receives approximately 150,000 – 200,000 tons of waste per year. The whole area is 70 hectares, of which 8.3 hectares are for functioning landfill and 23 hectares for closed landfill, both with methane capture and ground water control. The rest of the area is for the sorting and utilization facilities and only 10 per cent of waste is placed in landfill (PHJ 2011).

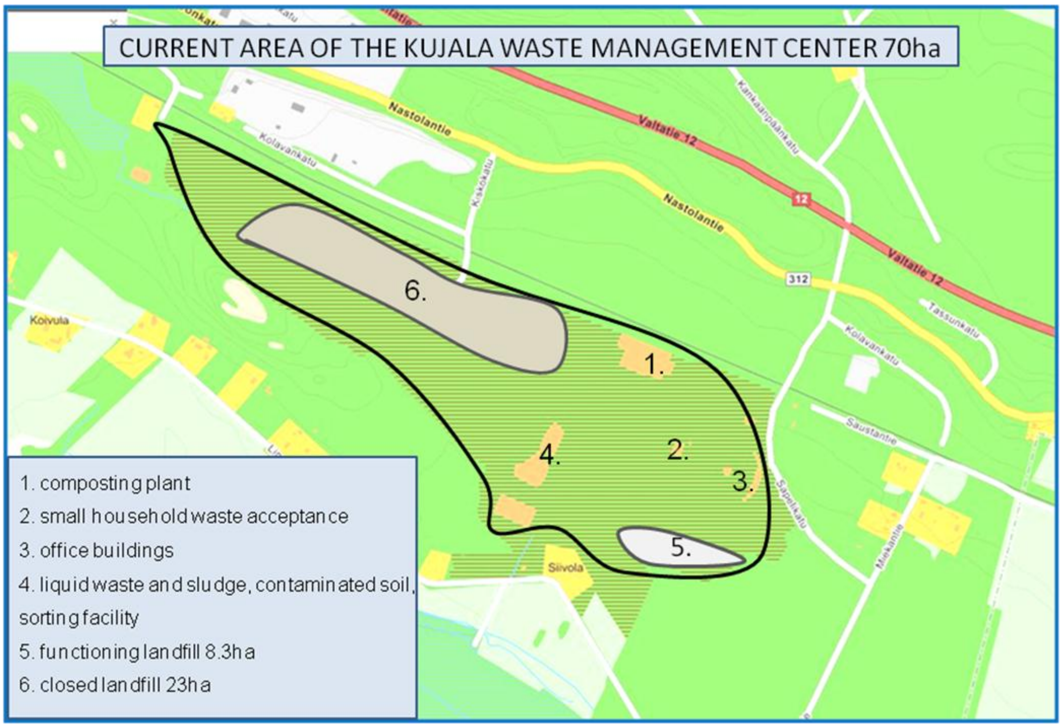


Figure 4. Current area of the Kujala Center 70 ha (modified from PHJ 2010; Eniro 2011; PHJ 2011; Kujalan Komposti Oy 2011)

4.2 Environmental Impact Assessment

In the Kujala Center, organic waste is managed by the Kujalan Komposti Oy composting plant. Kujala Oy was founded by PHJ and Lahti’s water service company Lahti Aqua Oy. Kujala Oy receives approximately 40,000 tons of bio waste per year from its clients and the Lahti region. Kujala Oy is planning to improve the processing of biodegradable waste and to increase the amount of waste it receives. This is reasonable as European directives (1999/31/EY) increase the restrictions to landfill proved waste (European Union 2010). A law-enforced environmental impact assessment (later referred to as EIA) has started in the Kujala Center to analyze the possible effect of the renovations on people, nature and surroundings (Kujalan Komposti Oy 2011; PHJ 2011).

The EIA includes different kinds of processes and solutions for biowaste processing. A biogas plant, a bioethanol plant and a microalgae cultivation facility are taken into consideration in addition to the existing compost plant (Kujalan Komposti Oy 2011).

A composting plant transforms organic waste back into soil substance which can be used for example as a fertilizer in gardening and crop fields. Composting is a natural aerobic process that produces heat, CO_2 and water as a side output. A biogas plant is based on an anaerobic process where organic waste is digested to produce biogases such as CO_2 and methane. Methane is an energetic greenhouse gas that can be burnt and utilized as natural gas. Nutrient rich wastewater, called reject, is formed during the process. The use of microalgae cultivation in waste management is a newer concept. Microalgae can grow by using nutrients that certain wastewaters have. Microalgae purify wastewater by using the phosphorus and nitrogen from the water. Phosphorus and nitrogen are the main causes of eutrophication in natural waters. Ruiz-Marin et al. (2009) reports nutrient removal percentages as high as 95 per cent for nitrogen, with an average of 80 per cent, and 80 per cent for phosphorus, with an average of 71 per cent. As a result of this, wastewater quality improves and takes away the pressure from the wastewater treatment plants and water systems. As microalgae use nutrients, their biomass increases and can be harvested for input material for a biogas plant and a bioethanol plant (Ruiz-Marin et al. 2009; Kujalan Komposti Oy 2011).

The improvement of processing biodegradable waste will increase the capacity of waste management in the Kujala Center. At the moment, the composting process handles 40,000 tons of biowaste per year. 20,000 tons come from industry, grocery stores and households and the other 20,000 tons is digested and undigested sludge from wastewater treatment plants. According to the new scheme, the capacity to handle biowaste will increase to 120,000 tons per year. This consists of wastewater from agriculture, forestry, fishery, gardening, households, grocery stores and industry. Kujala Oy also offers its services to other districts as a solution for a law-enforced bio waste management. A significant role is set to the microalgae cultivation and its potential as provider of biomass to biofuel production. A 2.2 hectare area is reserved for the microalgae cultivation facilities (see Figure 5). Main portion of the organic waste is planned to be handled in a biogas plant or in a bioethanol plant – the composting plant will continue to process mainly the sludge and residual from other processes (Kujalan Komposti Oy 2011). The Figure 5 shows the area reserved in EIA.

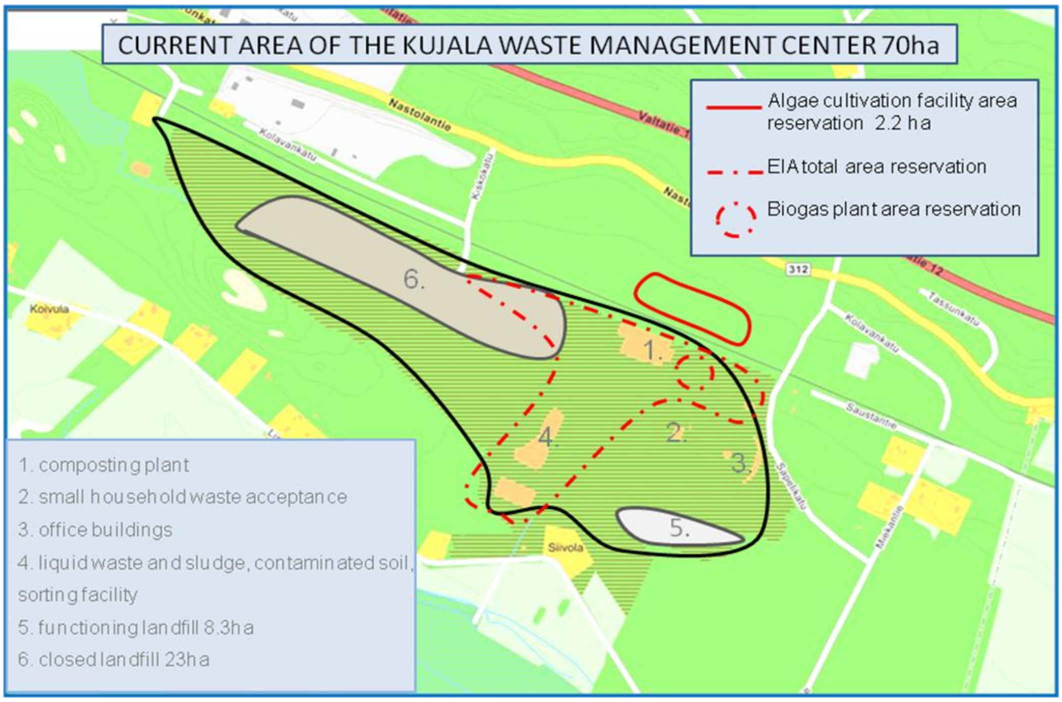


Figure 5. Reserved areas for renovations in EIA (modified from PHJ 2010; Eniro 2011; PHJ 2011; Kujalan Komposti Oy 2011)

4.3 ALDIGA’s concept of a closed circulation

The concept of ‘a closed circulation’ will be applied in the renovations of Kujala Oy’s biowaste management. Figure 6 shows how different processes benefit from each other by recycling their material and rejects and by utilizing by-products.

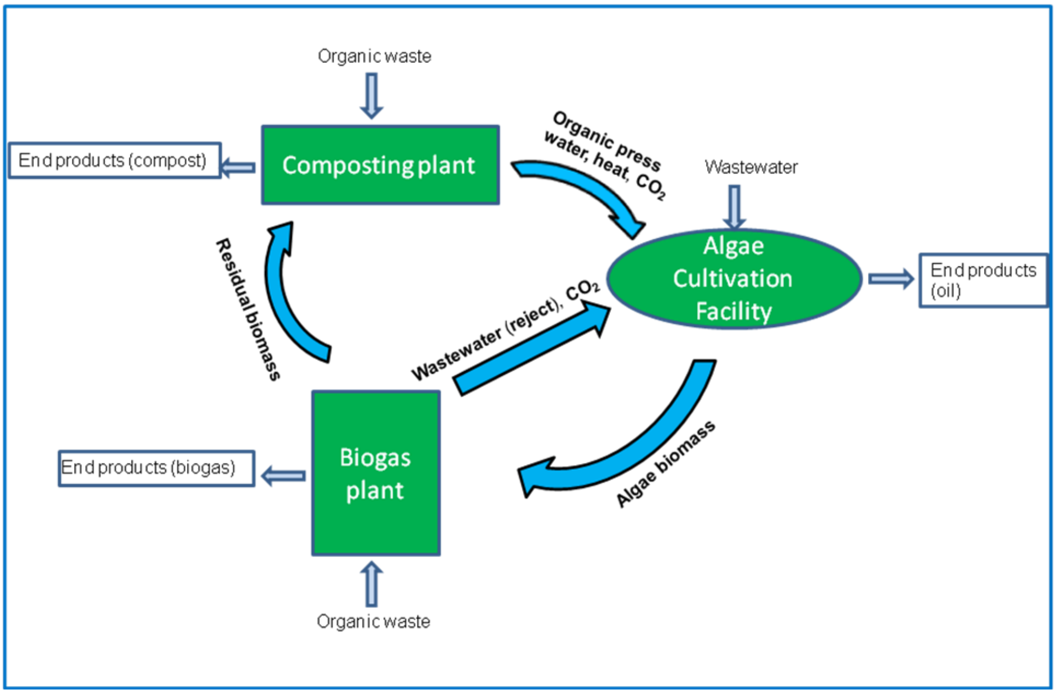


Figure 6. The concept of closed circulation between different processes (ALDIGA 2011a)

The composting plant, the biogas plant and the microalgae cultivation facility are planned to function together in a closed circulation. Microalgae biomass is used as a raw material in the biogas plant. Before this, lipids can be extracted from the microalgae biomass and utilized as raw material for biodiesel production. Biomass will be digested with other organic waste to produce CO_2 and methane. The biomass residual from the biogas plant will be further processed in the composting plant. The digestion process produces nutrient rich reject, which is directed back to the microalgae cultivation. Heat and CO_2 are required when cultivating microalgae. The composting process produces heat, CO_2 and nutrient rich organic press water, which can be directed to the microalgae cultivation. CO_2 from biogas plant can also be utilized (ALDIGA 2011a).

When using the concept of closed circulation, the required parameters for microalgae cultivation (CO_2, heat, nutrients) are available locally and cost-efficiently. This is a valuable benefit in order to make the cultivation as cost-efficient as possible.

5 SCENARIOS

Optimized microalgae cultivation is location and environment sensitive and drawing conclusions to a single situation must be done with caution. The three scenarios give a meaningful modeling by evaluating minimum and maximum limits rather than exact numbers. This gives a range and understanding what algae cultivation would mean in the Kujala Center in terms of biomass productivity, area requirement and water consumption.

The scenarios are based on certain parameters, concepts, calculations and assumptions (see Chapter 5.1). These are constructed from a large amount of information from many sources such as experiment data from the ALDIGA research team (UH), and scientific publications.

5.1 Base model for the scenarios

The modeling is based on the available 2.2 hectare land area which is reserved in the EIA (see Chapter 4.2). The scenarios evaluate the biomass productivity and water consumption according to this area limitation. This is done with ALDIGA’s concept of the six-day harvesting model explained in Chapter 5.1.1 (ALDIGA 2011b) and with collected data on the productivity rates of microalga strains. Certain parameters are excluded from the evaluation or used as constant values (see Chapter 5.1.3).

5.1.1 ALDIGA six-day harvesting model

Microalga that reaches its optimal harvesting density in approximately six days is cultivated in a system of six containers. Graduated cultivation is managed in periods of one container per day as shown in Figure 7. This way harvesting is done continuously seven days a week. Daily harvesting is justifiable as the pressure of malfunctioning and processing phases is spread for the whole week.

Two thirds of the container volume is removed during the microalgae harvesting. Microalgae grow mixed in the cultivation water so one third of water and microalgae remain in the container after harvesting. This is meaningful as a portion of the growth is needed to keep the cultivation on (ALDIGA 2011a; ALDIGA 2011b; Quinn et al. 2011).

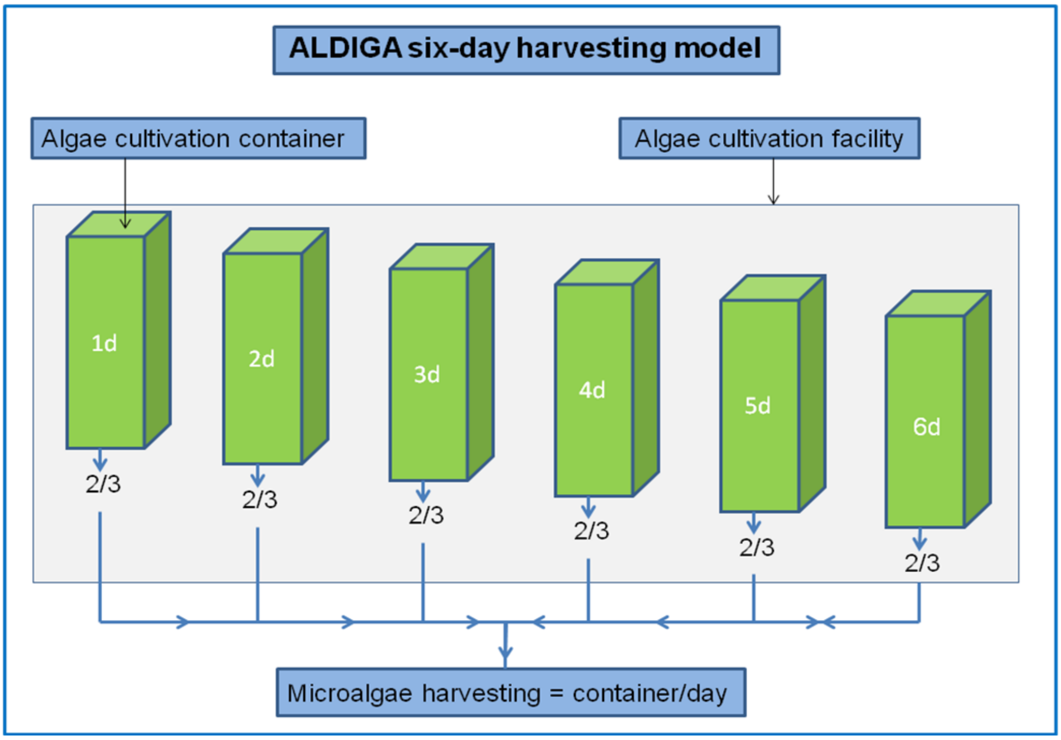


Figure 7. Sketch of the ALDIGA six-day harvesting model (ALDIGA 2011a)

5.1.2 Productivity rate of microalga strains

In this thesis the cultivation is carried out with *Chlorella sp.* microalga strains. ALDIGA research team (UH) has tested promising mixotrophic strains such as *Chlorella Protothecoides* and *Chlorella Pyrenoidosa* for Finnish circumstances (ALDIGA 2011a; ALDIGA 2011b). These are also internationally studied strains for their promising potential in bioenergy applications. ALDIGA's experiment data and peer-reviewed data from literature are used to collect productivity rates of microalgae and to apply them in the scenarios. Productivity is expressed in different ways depending on the source. One way is to tell the harvesting density of the microalga (Mata et al. 2009). This is the optimal amount of microalgae in the cultivation solution at a certain time. It is usually expressed in grams per liter per day. For example 5 grams per liter per day means that the microalgae are cultivated in one liter to five gram density in one day. Harvesting density is not usually the maximum density but the optimized situation where the exponential growth is passed. Higher densities are possible to obtain but is not meaningful in optimized biomass production.

Harvesting density is the amount of biomass that is produced per volume per time. Harvesting *yield* tells the actual amount of biomass that is removed in the harvesting. It is calculated by multiplying the harvesting density by two thirds (the harvesting portion). It is also represented by weight per volume per day value. For example, in the 5 grams per liter per day, the harvesting yield would be 3.3 grams per liter per day (1).

$$(1)\quad 5.00\ \mathrm{g/L/d} * \tfrac{2}{3} = 3.33\ \mathrm{g/L/d}$$

5.1.3 Excluded parameters and constant values

In this thesis a necessary screening and simplification of used parameters has been done. Thorough modeling with all effecting parameters would require far more extensive work and research than is reserved for a Bachelor’s thesis. The role of illumination, CO_2, nutrients and heat variation are not examined is this work. Because of this, the selection between autotrophic and heterotrophic cultivation is also excluded. Both processes are possible as the used strains such as *Chlorella protothecoides* and *Chlorella pyrenoidosa* are mixotrophic (ALDIGA 2011a).

The depth of a cultivation container is considered to be a constant value of 0.2 meters. This value is used broadly in literature. Any higher depth would block effective illumination and disturb the microalgae growth. Microalgae are able to grow in nutrient rich wastewaters but raw wastewater is often too strong to be used solely. A 1/10 dilution, based on experimental data of Kujala Oy’s wastewater streams (ALDIGA 2011b), is used in this study. The containers are situated in the cultivation facility in a certain way with a constant two meter safe zone around them. A 0.2 hectare area is reserved for processing facilities in every scenario. The cultivation is modeled to function 365 days a year. These three values are personal estimations.

5.2 Worst-case scenario

The worst-case scenario models the Kujala Center with the most cautious values and strives to point out the microalgae cultivation performance at its lowest point. Before calculating the microalgae biomass productivity and water consumption, the layout and volume of the containers is solved for the 2.2 hectares (2).

(2) Dimensions of the containers and 2.2 hectare area

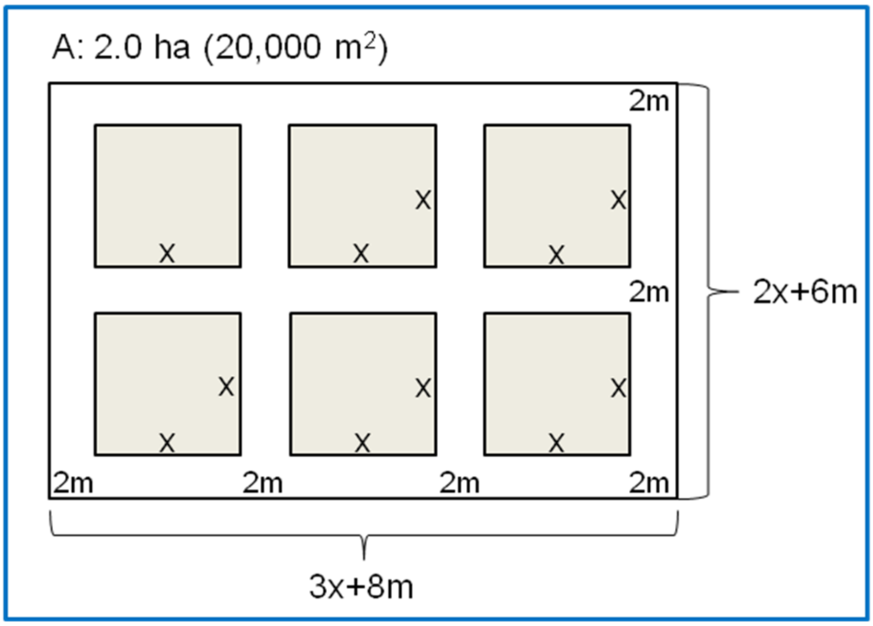


Figure A. Solving the dimensions of containers and their area

$(3x+8) * (2x+6) = 20{,}000$

$X_1 = 54.9$

$X_2 = -60.6$ (irrelevant)

See Figure B for solved dimensions.

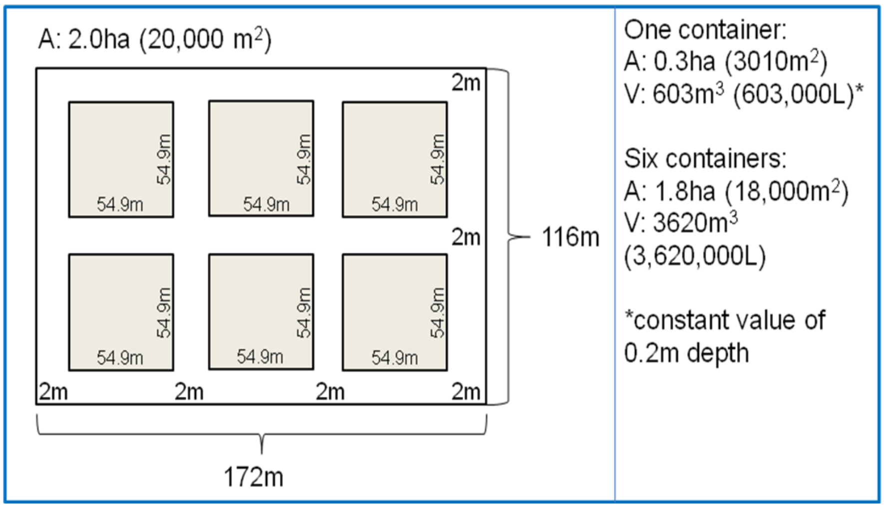


Figure B. Solved dimension for the containers and their area

See Figure C for the dimension for the whole area with the 0.2 hectare reservation for processing facilities.

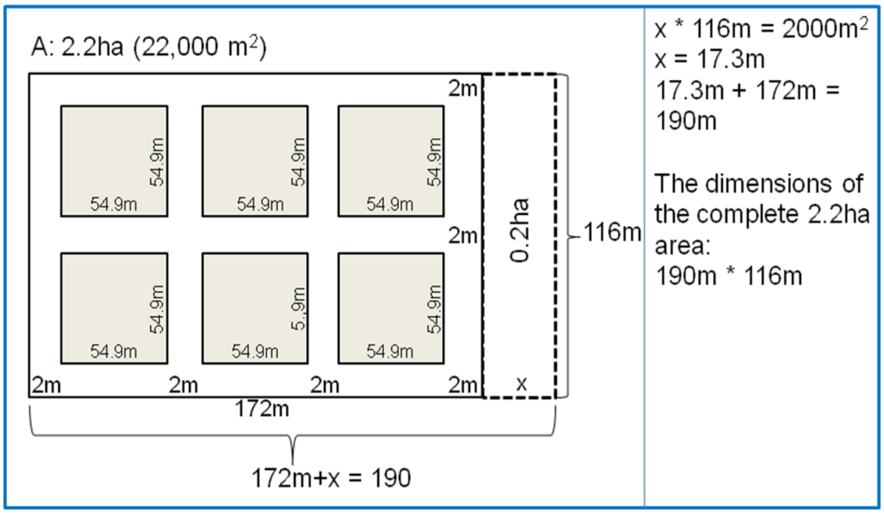


Figure C. Dimensions for the whole 2.2 ha area.

(See appendices for detailed calculations.)

The 2.2 hectare area fits six 0.3 hectare containers with the volume of 603 cubic meters. These dimensions are used in all scenarios.

A low harvesting density of 0.6 grams per liter per six days is selected to the Worst-case scenario. This is an average of the lowest values found in the literature (Mata et al. 2009; Shen et al. 2009; Chen et al. 2010; Hulatt et al. 2011). These values were achieved either in autotrophic, heterotrophic or mixotrophic cultivation. The biomass productivity for the 0.3 hectare containers is calculated (3).

(3) Biomass productivity in the Worst-case scenario

The harvesting yield: 0.6 g/L/6d * ⅔ = 0.4 g/L/6d

Volume of one container: 603 m^3 (603,000 liters)

0.4 g/L/6d * 603,000 L = 241,000 g/6d (0.241 t/6d)

Six progressed containers = 0.241 t/d

Yield per year: 0.241 t/d * 365d = 88.0 t/a

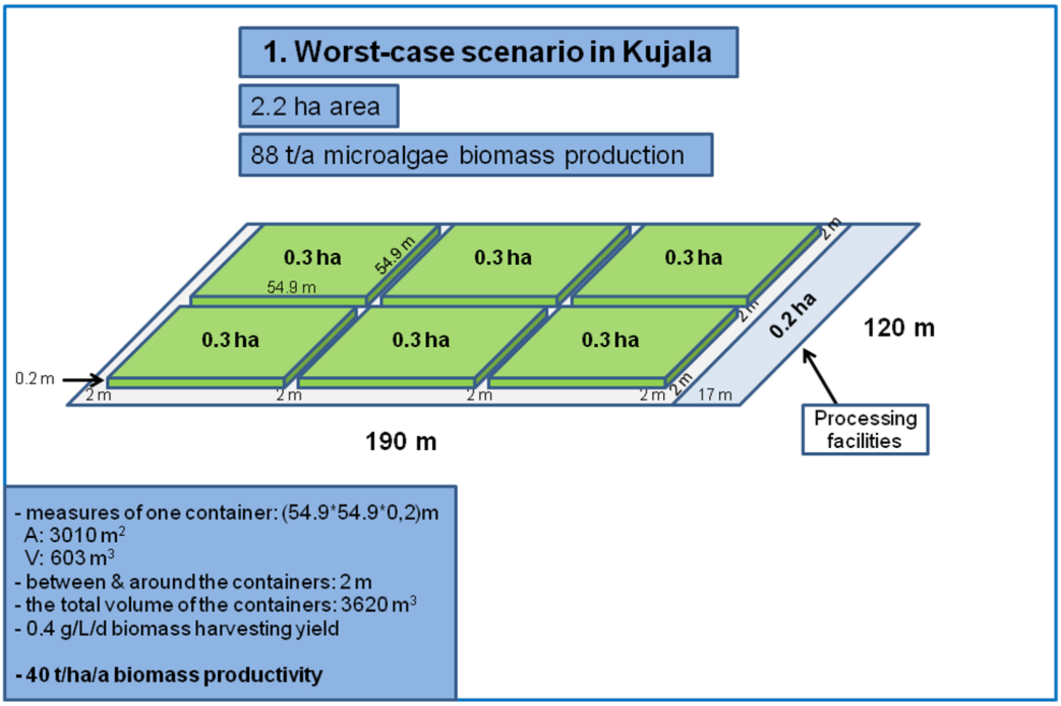
2.2 hectare area produces 88.0 tons per year.

[2.2 ha = 88.0 t/a] [1.0 ha = x t/a]

2.2x = 88.0

x = 40.0

The biomass productivity in the Worst-case scenario is 40.0 t/ha/a.



- measures of one container: (54.9*54.9*0,2)m
  A: 3010 m^2
  V: 603 m^3
- between & around the containers: 2 m
- the total volume of the containers: 3620 m^3
- 0.4 g/L/d biomass harvesting yield

- 40 t/ha/a biomass productivity

Figure 8. A sketch of the capacity and potential in the Worst-case scenario

In order to reduce water consumption, water from the microalgae harvesting is recycled back to the system. Because of the uptake of nutrients by microalgae, this water can be used to dilute the raw wastewater input to the 1/10 dilution. This way the majority of the total water circulation in the system is managed with the existing water. In the Worst-case scenario though, evaporation is included in the modeling. This is done to examine the effect it has on water consumption. The required amount of water is calculated (4).

(4) Water consumption in the Worst-case scenario

An initial input of water is required when the microalgae cultivation is started for the first time. This is the volume of all six containers:

$603\ m^3 * 6 = 3620\ m^3$ (3,620,000 L)

As microalgae is cultivated in a 1/10 dilution, $362\ m^3$ of the initial input is raw input and $3000\ m^3$ is diluted water.

Two thirds of one container volume is removed every day during the harvesting:

$603\ m^3/d * ⅔ = 402\ m^3/d$

This water is circulated back to the system with the portion of raw input:

(x = the added amount of raw input)

$x * 10 = 402\ m^3/d$

$x = 40.2\ m^3/d$

$402 m^3/d – 40.2 m^3/d = 362\ m^3/d$

The harvested $402\ m^3/d$ amount of water is replaced with $362\ m^3/d$ of circulated water from the system and $40.2\ m^3/d$ of new raw input.

Raw input: $14700\ m^3/a$

Evaporation:

Evaporation from a water system can be 2-3 per cent (Kuusisto 2011; Pate 2011). An average of 2.5 per cent evaporation is used when calculating the evaporation from six containers:

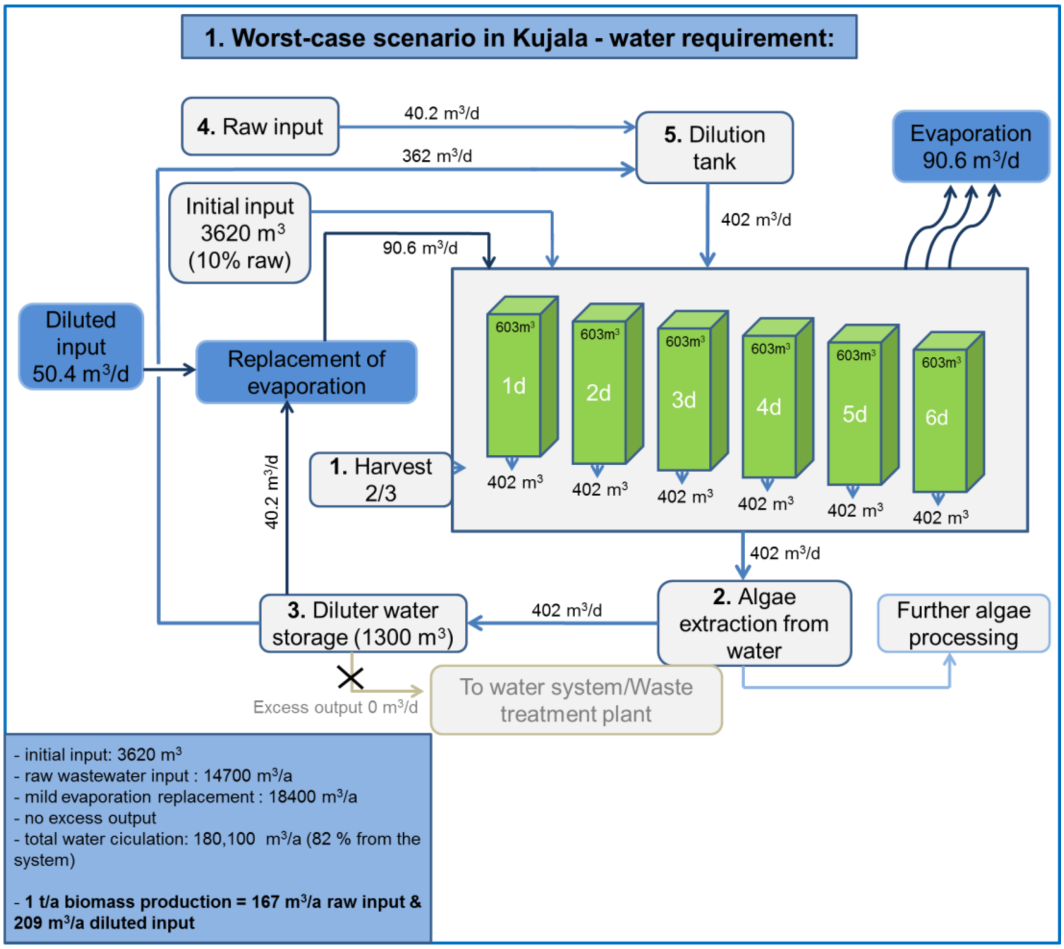
$(603\ m^3/d * 0.025) * 6 = 90.6\ m^3/d$

This evaporation loss is replaced partly with the excess output from cultivation and new diluted input.

Excess 40.2 m^3/d of water remains after the 362 m^3/d is circulated back to the system for the biomass harvesting.
90.6m^3/d – 40.2m^3/d = 50.4m^3/d
50.4 m^3/d (18400 m^3/a) of diluted input water is needed to fully replace the evaporation. Because of the evaporation replacement, no excess water output comes from the cultivation system.

The ratio between produced biomass and consumed water:
Raw input: [88 t/a = 14700 m^3/a] [1 t/a = x]
88x = 14700
x = 167
Evaporation replacement: [88 t/a = 18400 m^3/d] [1 t/a = x]
x = 209
1 t/a microalgae biomass production requires 167 m^3/a raw input & 209 m^3/a diluted evaporation replacement.

The total water circulation in the system is 180,100 m^3/a (82 per cent of reused dilution water from the system).



- initial input: 3620 m^3
- raw wastewater input : 14700 m^3/a
- mild evaporation replacement : 18400 m^3/a
- no excess output
- total water ciculation: 180,100 m^3/a (82 % from the system)

- **1 t/a biomass production = 167 m^3/a raw input & 209 m^3/a diluted input**

Figure 9. A sketch of water consumption in the Worst-case scenario

5.3 Moderate scenario

A moderate harvesting density of 3.0 grams per liter per six days is selected to the Moderate scenario. This is a total average of the values found in the literature (Ugwu et al. 2007; Mata et al. 2009; Shen et al. 2009; Chen et al. 2010; Hulatt et al. 2011) and the experiment data from ALDIGA research team (UH) (ALDIGA 2011a). These values were achieved either in autotrophic, heterotrophic or mixotrophic cultivation. The biomass productivity for the 0.3 hectare containers is calculated (5).

(5) Biomass productivity in the Moderate scenario
The harvesting yield: 3.0 * ⅔ = 2.0 g/L/6d
Volume of one container: 603,000 liters.
2.0 g/L/6d * 603,000 L = 1,206,000 g/6d (1.21 t/6d)
Six progressed containers = 1.21 t/d

Yield per year: 1.21 t/d * 365d = 442 t/a

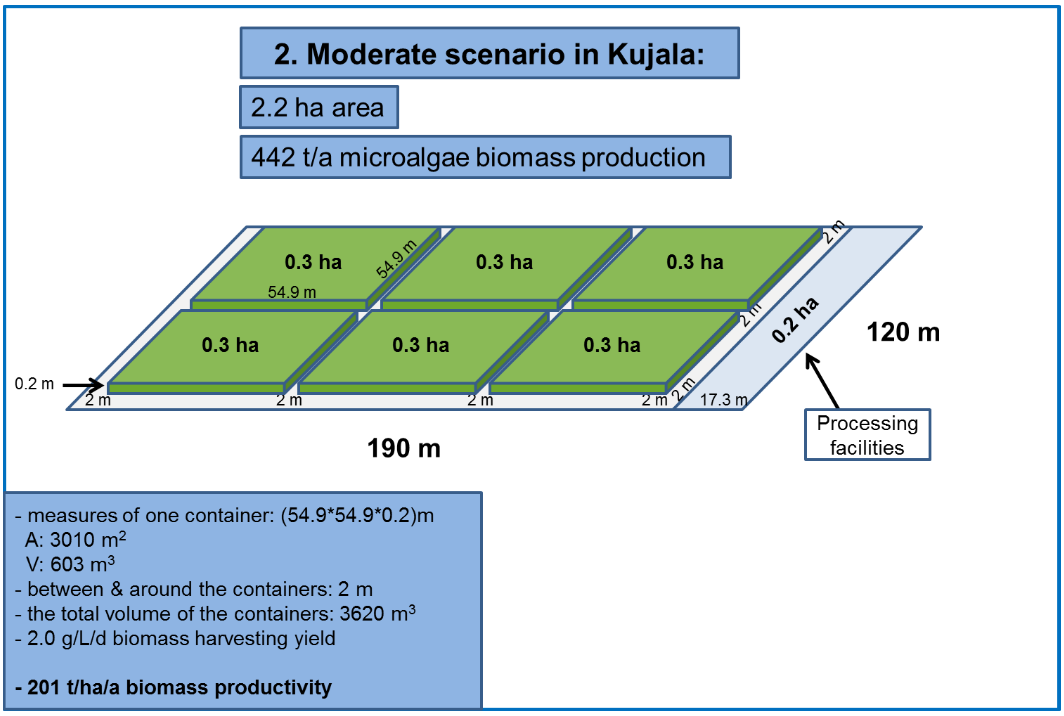
2.2 hectare area produces 442 tons per year.

[2.2 ha = 442 t/a] [1.0 ha = x t/a]

2.2x = 442

x = 201

The biomass productivity in the Moderate scenario is 201 t/ha/a.



2. Moderate scenario in Kujala:

2.2 ha area

442 t/a microalgae biomass production

- measures of one container: (54.9*54.9*0.2)m
  A: 3010 m^2
  V: 603 m^3
- between & around the containers: 2 m
- the total volume of the containers: 3620 m^3
- 2.0 g/L/d biomass harvesting yield

- 201 t/ha/a biomass productivity

Figure 10. A sketch of the capacity and potential in the Moderate scenario

Water consumption per time is the same as in the Worst-case scenario (see (3)) except that no evaporation loss appears in the Moderate scenario. This means that excess water output appears. The consumption according biomass production and excess output is calculated (6).

(6) Water consumption in the Moderate scenario

As 90 per cent of water from the harvesting phase is recycled, excess of 10 per cent appears. This is the same amount of water as is the raw input. 40.2 m^3/d raw input replaces 40.2 m^3/d of the diluted water.

Excess output: 40.2 m^3/d * 365 = 14700 m^3/d

The ratio between produced biomass and consumed water:

Raw input: [442 t/a = 14700 m^3/a] [1 t/a = x]

442x = 14700

x = 33.3

Water consumption in the Moderate scenario: 1 t/a microalgae biomass = 33.3 m^3/a raw input.

The total water circulation in the system is 147,000 m^3/a (90 per cent of reused dilution water from the system).

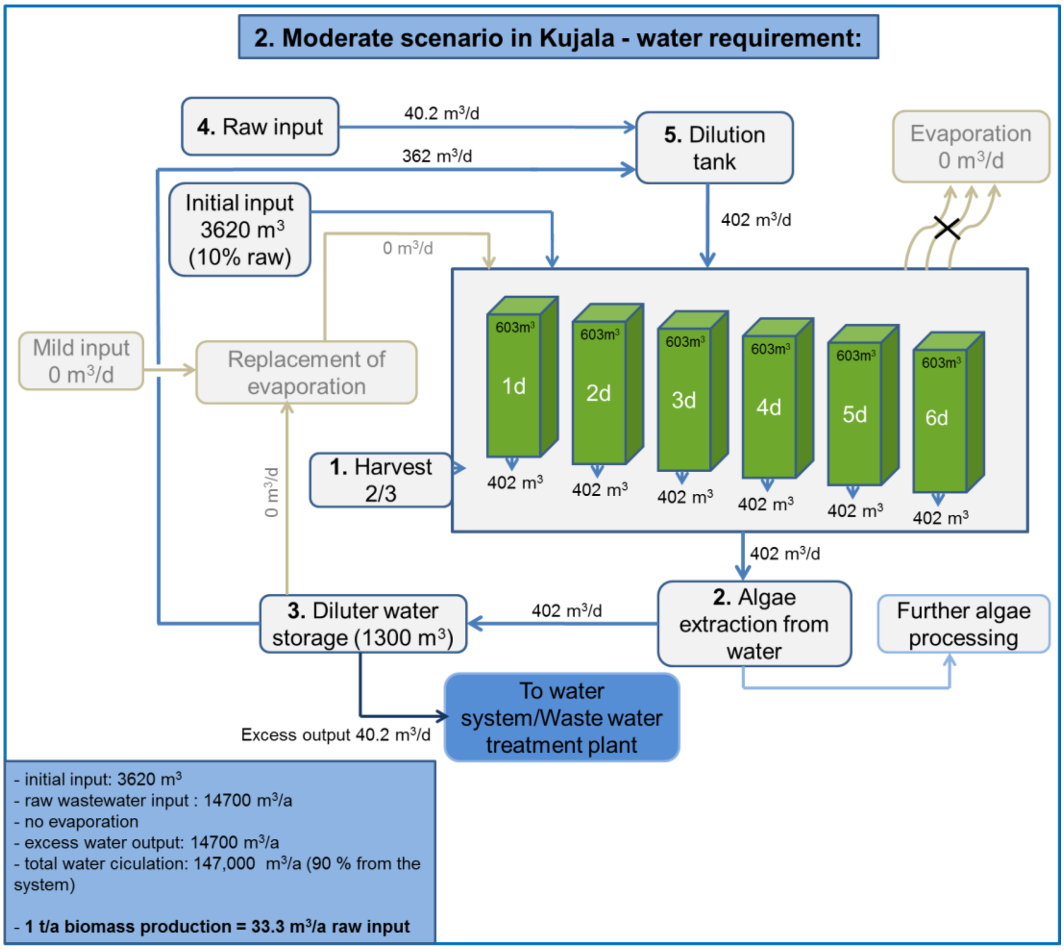


Figure 11. A sketch of water consumption in the Moderate scenario

5.4 Optimal scenario

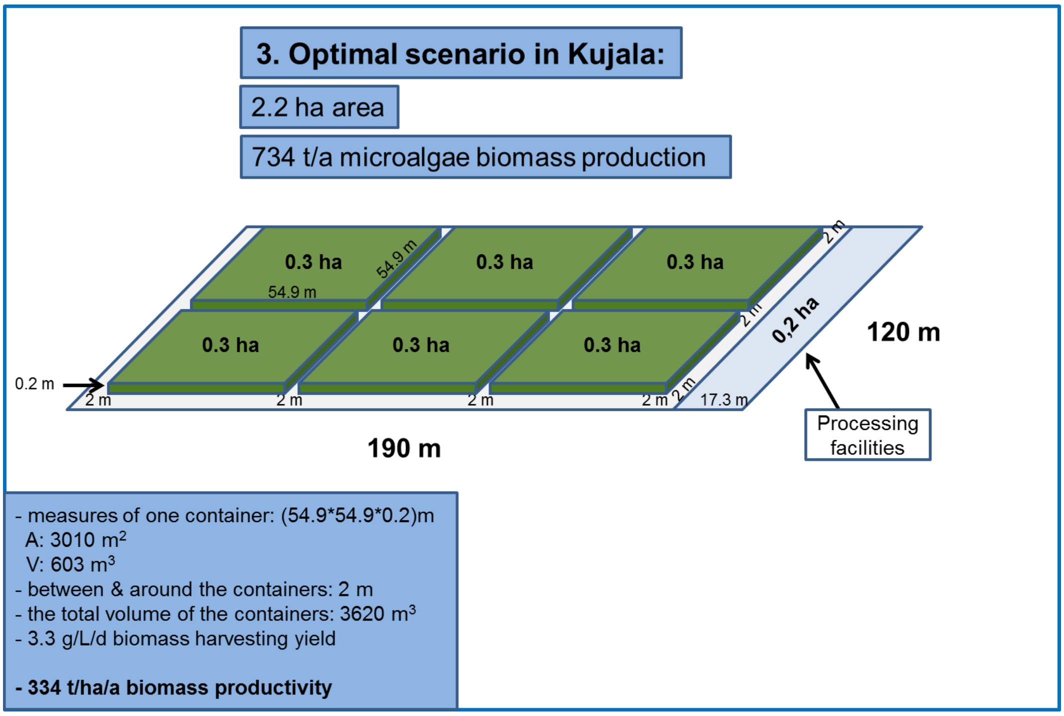
The Optimal scenario models the Kujala Center with the most optimal values and strives to point out the microalgae cultivation performance at its highest point in the Kujala Center.

An optimal harvesting density of 5.0 grams per liter per six days is selected to the Optimal scenario. This is an average of the maximum values found in the literature (Mata et al. 2009; Shen et al. 2009; Chen et al. 2010; Hulatt et al. 2011). These values were achieved either in autotrophic, heterotrophic or mixotrophic cultivation. A harvesting density 15 grams per liter per six days (Xu et al. 2006) was recognized but excluded as an isolated peak result. The biomass productivity for the 0.3 hectare containers is calculated (7).

(7) Biomass productivity in the Optimal scenario
The harvesting yield: 5 g/L/6d * ⅔ = 3.33 g/L/6d
Volume of one container: 603,000 liters
3.33 g/L/6d * 603,000 L = 2,008,000 g/6d (2.01 t/6d)
Six progressed containers = 2.01 t/d

Yield per year: 2.01 t/d * 365d = 734 t/a

2.2 hectare area produces 734 tons per year.
[2.2 ha = 734 t/a] [1.0 ha = x t/a]
2.2x = 734
x = 334
The biomass productivity in the Optimal scenario is 334 t/ha/a.



3. Optimal scenario in Kujala:

2.2 ha area

734 t/a microalgae biomass production

- measures of one container: (54.9*54.9*0.2)m
  A: 3010 m^2
  V: 603 m^3
- between & around the containers: 2 m
- the total volume of the containers: 3620 m^3
- 3.3 g/L/d biomass harvesting yield

- 334 t/ha/a biomass productivity

Figure 12. A sketch of the capacity and potential in the Optimal scenario

Water consumption per time is the same as in the Moderate scenario (see (6)). The consumption according biomass production differs and is calculated (8).

(8) Water consumption in the Optimal scenario

The ratio between produced biomass and consumed water:

Raw input: [734 t/a = 14700 m^3/a] [1 t/a = x]

734x = 14700

x = 20.0

Water consumption in the Optimal scenario: 1 t/a microalgae biomass = 20.0 m^3/a raw input.

The total water circulation in the system is 147,000 m^3/a (90 per cent reused dilution water from the system).

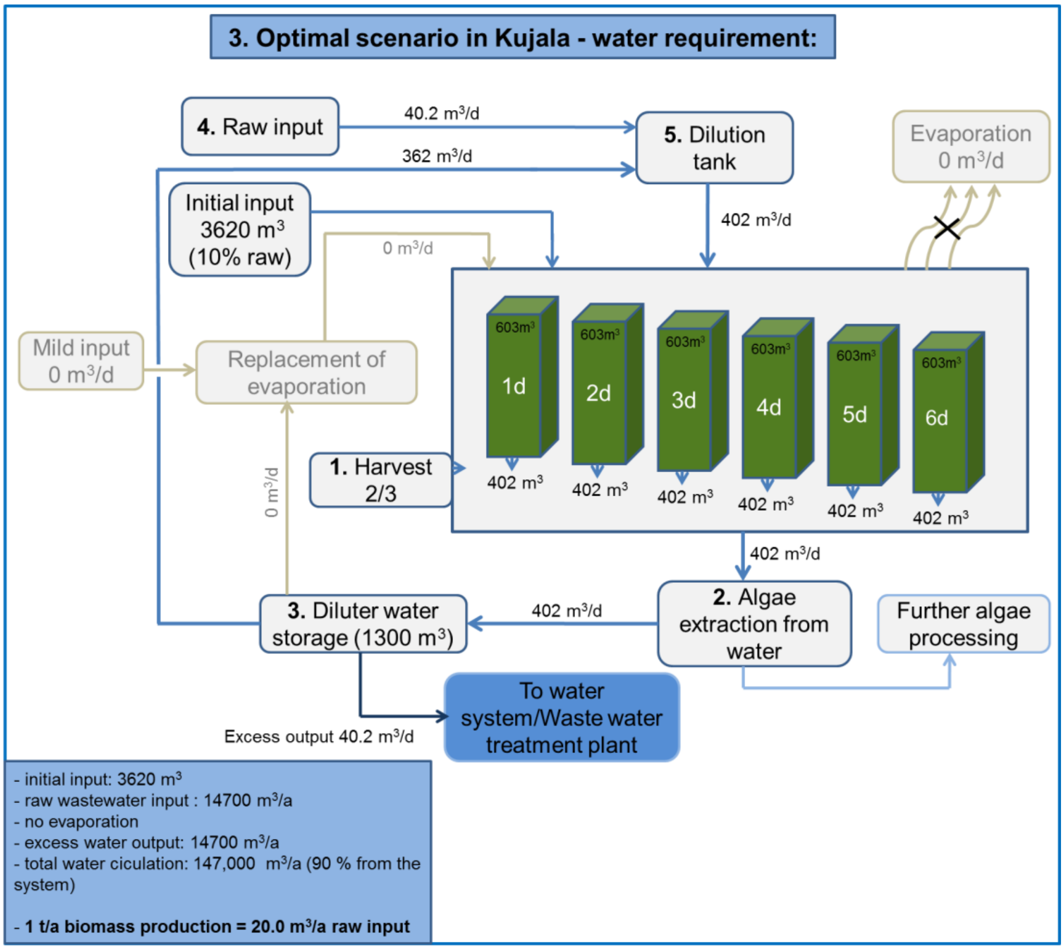


Figure 13. A sketch of water consumption in the Optimal scenario

5.4.1 Optimal scenario – Alternative approach

The Alternative approach examines the effect a layered cultivation model has on biomass production and water consumption. In layered cultivation, containers are built in storeys in order to save space and increase the productivity per hectare (see Figure 14).

The Alternative approach is based on the Optimal scenario but two extra layers of cultivation containers are built. This basically triples the biomass production and water consumption but productivity per hectare is increased (9).

(9) Biomass production and water consumption in the Alternative approach

Yield per year: 734 t/a * 3 = 2200 t/a

2.2 hectare area produces 2200 tons per year.
[2.2 ha = 2200 t/a] [1.0 ha = x t/a]
2.2x = 2200
x = 1000

The biomass productivity of the Alternative approach is 1000 t/ha/a.

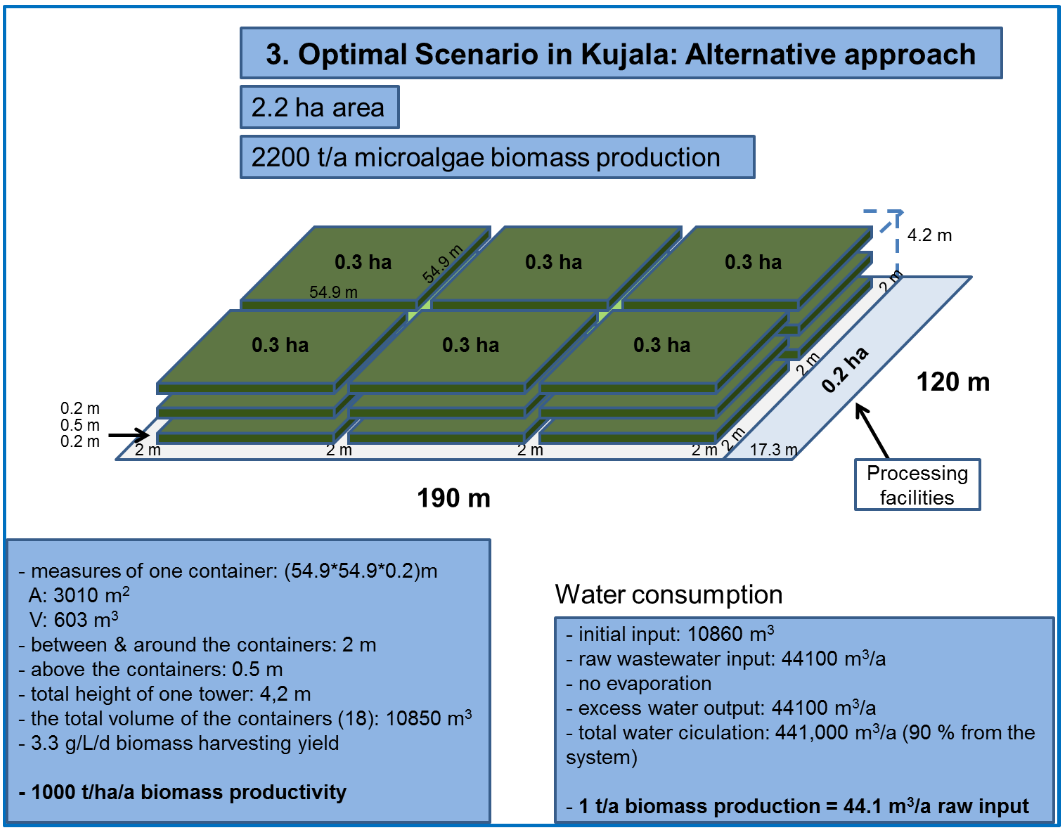
Water consumption
An initial input of water:
3620 m^3 * 3 = 10860 m^3

Raw input: 14700 m^3/a * 3 = 44100 m^3/a
Excess water output: 14700 m3/a * 3 = 44100 m^3/a

The ratio between produced biomass and consumed water:
Raw input: [1000 t/a = 44100 m^3/a] [1 t/a = x]
1000x = 44100 m^3/a
x = 44.1 m^3/a

Water consumption in the Alternative approach: 1 t/a microalgae biomass = 44.1 m^3/a raw input.

The total water circulation in the system is 441,000 m^3/a (90 per cent reused dilution water from the system)



- measures of one container: (54.9*54.9*0.2)m
  A: 3010 m^2
  V: 603 m^3
- between & around the containers: 2 m
- above the containers: 0.5 m
- total height of one tower: 4,2 m
- the total volume of the containers (18): 10850 m^3
- 3.3 g/L/d biomass harvesting yield

- 1000 t/ha/a biomass productivity

Water consumption

- initial input: 10860 m^3
- raw wastewater input: 44100 m^3/a
- no evaporation
- excess water output: 44100 m^3/a
- total water ciculation: 441,000 m^3/a (90 % from the system)

- 1 t/a biomass production = 44.1 m^3/a raw input

Figure 14. A sketch of the capacity, potential and water consumption in the Alternative approach

5.5 Summary of the scenarios

The results are assembled to Table 1 and to Table 2. 10 hectare model and 60,000 tons per year model are included in the tables to analyze the scenario results. Kujala Oy’s reservation for microalgae cultivation is located on an isolated forest plot size of 10 hectares (Eniro 2011). This area is zoned for industry and storage buildings in the city plan (Kujalan Komposti Oy 2011) and is located in an industrial area which excludes the recreational use of the forest plot. 10 hectare model examines microalgae biomass productivity in the whole 10 hectares area using the Alternative approach.

(10) Biomass productivity in the 10 ha model

Biomass productivity in the Alternative approach: 1000 t/ha/a

[1 ha = 1000 t] [10 ha = x t]

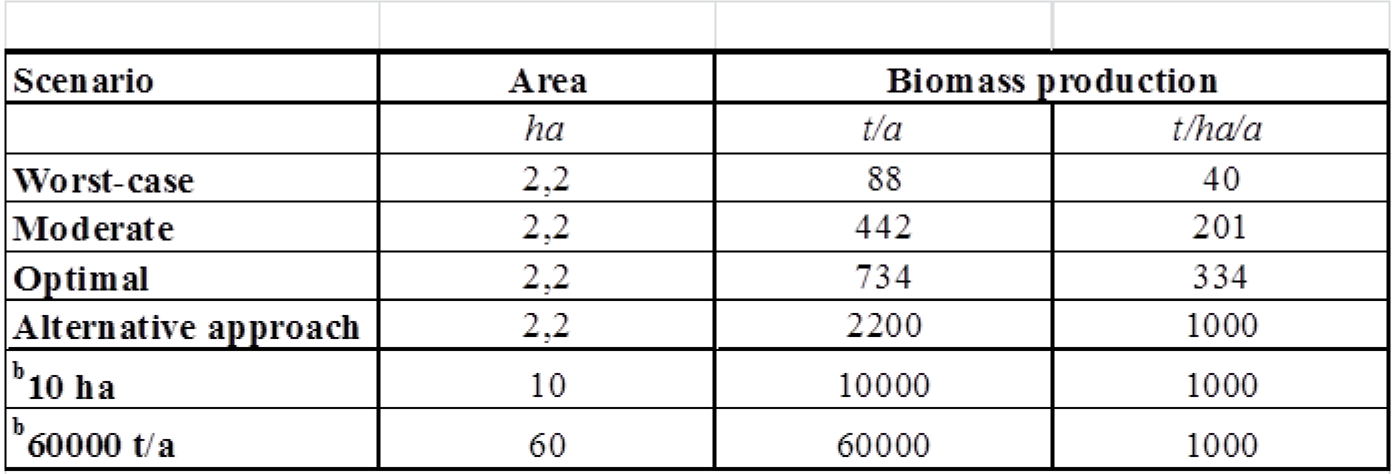
x = 10,000

10 ha = 10,000 t

60,000 tons per year biomass production from microalgae cultivation is desired in the Kujala Center, according to the Kujala Oy EIA report (Kujalan Komposti Oy 2011) and according co-operation with the Kujala Oy staff. 60,000 tons per year model examines how big an area would be required to this level production with the Alternative approach.

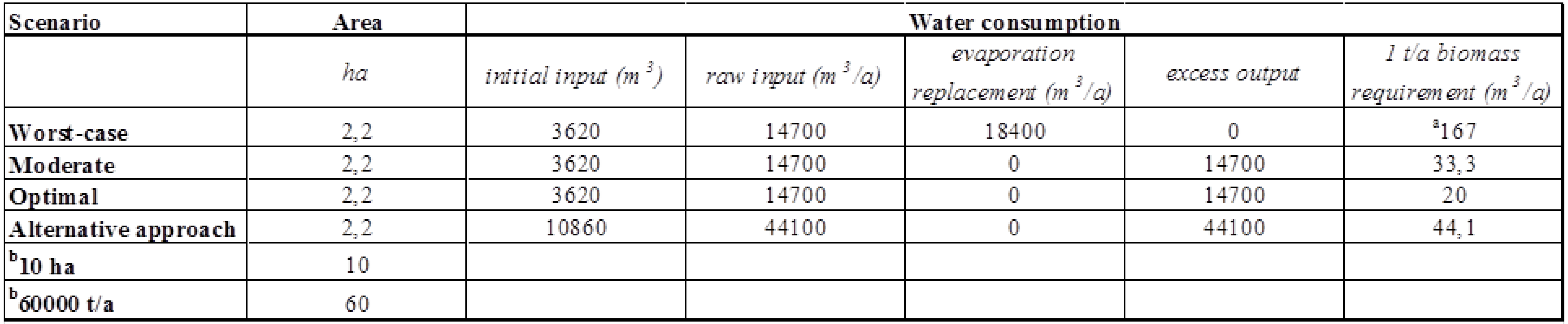
(11) Biomass productivity in 60,000 t/a model

Biomass productivity in the Alternative approach: 1000 t/ha/a
[1 ha = 1000 t] [x ha = 60,000 t]
1000x = 60,000
x = 60 ha
60,000 t/a require 60 hectares.



Scenario	Area	Biomass production	
	ha	*t/a*	*t/ha/a*
Worst-case	2,2	88	40
Moderate	2,2	442	201
Optimal	2,2	734	334
Alternative approach	2,2	2200	1000
[b]10 ha	10	10000	1000
[b]60000 t/a	60	60000	1000

Table 1. Biomass production of the scenarios. [b] with the Alternative approach, [a]with 209 m^3/a evaporation replacement



Scenario	Area	Water consumption				
	ha	*initial input (m^3)*	*raw input (m^3/a)*	*evaporation replacement (m^3/a)*	*excess output*	*1 t/a biomass requirement (m^3/a)*
Worst-case	2,2	3620	14700	18400	0	[a]167
Moderate	2,2	3620	14700	0	14700	33,3
Optimal	2,2	3620	14700	0	14700	20
Alternative approach	2,2	10860	44100	0	44100	44,1
[b]10 ha	10					
[b]60000 t/a	60					

Table 2. Water consumption of the scenarios. [b] with the Alternative approach, [a] with 209 m^3/a evaporation replacement

The three scenarios gave a range of the biomass productivity and water consumption that the Kujala Center are 2.2 hectare. According to the Worst-case scenario, the Kujala Center has the minimum potential of 88 tons per year microalgae biomass production. According to the Alternative approach the Kujala Center's maximum biomass productivity is 2200 tons per year. Table 1 shows that the productivity of the Alternative approach is many times higher than in the other scenarios. Productivity rates found in literature (Norsker et al. 2010: 64 t/ha/a; Stephens et al. 2010: 350 t/ha/a) correlate more with the Optimal scenario and the Worst-case scenario. The Alternative approach productivity rate can be considered to be too optimistic and more research must be done on the functionality of layered cultivations (see Chapter 5.4.1).

According to the study and literature, the 60,000 tons per year production rate is not possible in the Kujala Center's 2.2 hectare area. More cultivation space is required as the productivity per hectare cannot be increased. Table 1 (Appendices) indicates how a 10 hectare area would produce maximum of 10,000 tons of microalgae biomass per year (see Chapter 5.5). 60,000 ton yearly production would require 60 hectares even with the Alternative approach (this size microalgae cultivation center is being built for example in New Mexico, United States of America (Algae Industry Magazine.com 2011)).

According to Table 2 (Appendices), water consumption is highest in the Worst-case scenario due to the evaporation. A closed cultivation system is recommended in order to decrease the water consumption. On the other hand, excess water output appears in closed systems. The microalgae nutrient uptake has purified the waste water, which decreases the need for purification before charging it to water system. The Kujala Center's maximum demand for raw waste water is 44,100 cubic meters per year (the Alternative scenario). This is 0.5 per cent of Lahti's 8,760,000 cubic meters per year household wastewater production (Lahti Aqua 2011). Moreover, this is only 10 per cent of the total water demand the cultivation system has as the raw input is diluted with the solution water from the system.

6 DISCUSSION AND CONCLUSIONS

The study was based on certain assumptions and uncertainty factors that are important to acknowledge. These factors have a significant role when examining the accuracy of the results and conclusions. This way the reproducibility and applicability of the study are also examined. The most crucial factors are discussed below.

The possible variations of the constant factors in the scenarios affect the modeling and the results. In this thesis a non-stop production rate through the whole year (365 days) was used. In practice, there would be an undefined number of maintenance and malfunction days, which would stop the biomass production temporarily. The 0.2 hectare processing facility area and two meter safe zone value were kept in every scenario. These limit the size of the cultivation containers and affect the biomass production potential.

A decision between autotrophic, mixotrophic and heterotrophic cultivation, or the selection of open-pond, tubular or bioreactor containers, was left outside of this work. Important factors such as illumination, CO_2, nutrients and heat were also excluded. The Kujala Center and Kujala Oy have a capability to manage these in theory nonetheless (see Chapter 4.3).

One must be critical when examining the suitability of collected microalgae growth data to this thesis. A broad range of literature and data was analyzed and approximately 40 different microalgae growth values (*Chlorella sp*.) were gathered. Different ways to describe the biomass productivity complicated the data gathering and their applying to the Kujala Center situation. A more detailed analysis of the test result conditions in literature must be done. The majority of the data and results used in the thesis were also gained in laboratory-scale or pilot-scale experiments. Applying this data to industrial-scale microalgae cultivation includes a possibility of a big margin of an error. This is also one of the reasons for forming three scenarios rather than specifically defined numbers.

The aim of the study was to model the microalgae cultivation in the Kujala Waste Management Center with these scenarios. The focus was to examine the capacity and potential the Kujala Center has concerning biomass productivity, area requirement and water consumption.

The scenarios indicate that one of the Kujala Center's bottlenecks to the meaningful microalgae cultivation is lack of available area. It might be worth of considering to replace the objective of large-scale biomass production with other possible applications. These are for example optimized wastewater purification or production of other high value products. Optimized microalgae cultivation offers versatile utilization possibilities.

Many parameters and factors had to be excluded from this study as the microalgae cultivation modeling would have become too complex to carry out in a Bachelor's Thesis. Despite the uncertainty factors of this study, it succeeds to elucidate what the level of microalgae cultivation would be in the Kujala Center. The scenarios could be used for example as a base for further and more detailed modeling in the ALDIGA project and for the Kujala Oy's EIA. First step would be to include more vital parameters such as illumination and CO_2 and to model input - output energy and cost estimations. In this modeling level a use of a modeling tool such as SuperPro Designer would be meaningful.

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APPENDICES

Appendix 1. Detailed calculations

Appendix 1. Detailed calculations

(2) Dimensions of the containers and 2.2 hectare area

According to the six-day harvesting model (see Chapter 5.1), six cultivation containers are required. Containers are placed and dimensions solved according to Figure A.

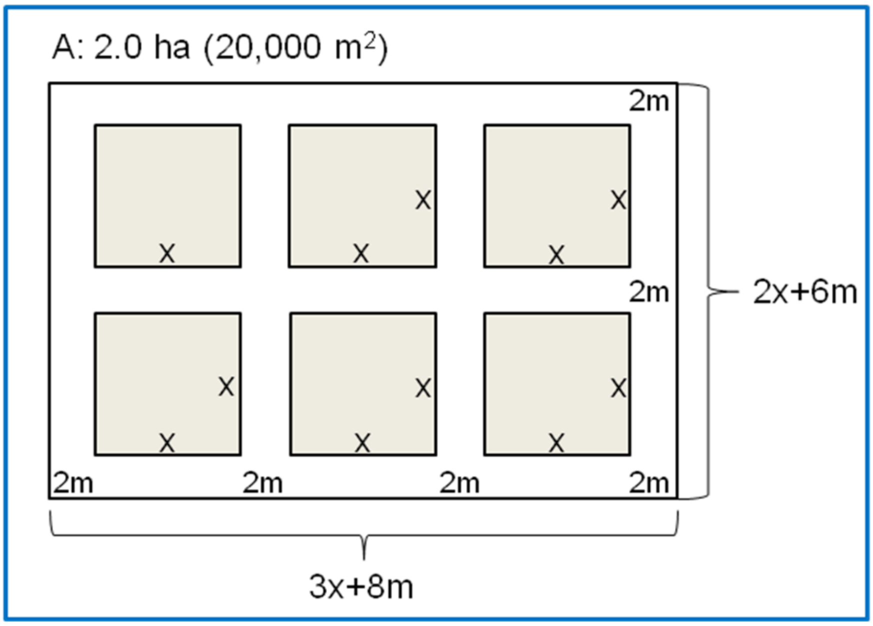


Figure A. Solving the dimensions of containers and their area.

$(3x+8) * (2x+6) = 20,000$

$6x^2 + 34x + 48 = 20,000$

$6x^2 + 34x – 19952 = 0$

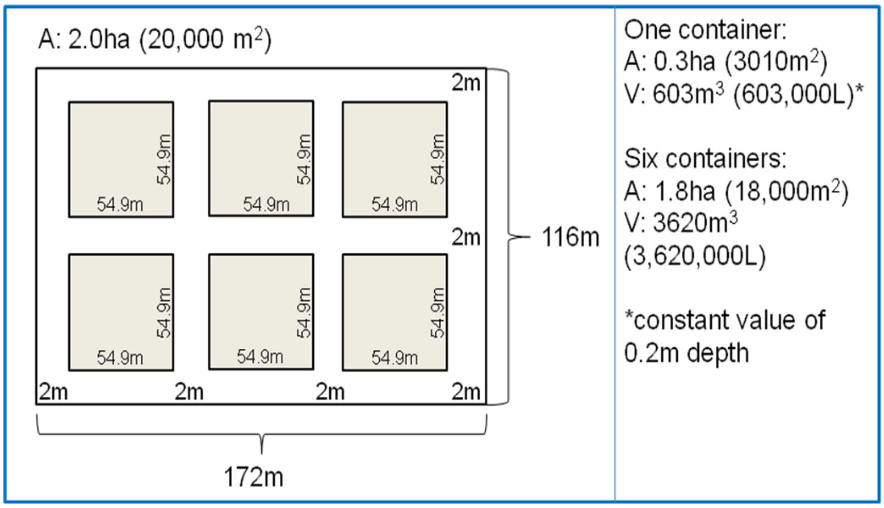
$a=6 \mid b=34 \mid c= (-19952) \mid x = [-b\pm\sqrt{}(b^2-4ac)] / 2a$

$[-34 \pm \sqrt{} [(34^2 – 4 * 6 * (-19952)]] / 2 * 6$

$X_1 = 54.9$

$X_2 = -60.6$ (irrelevant)

See Figure B. for solved dimensions.



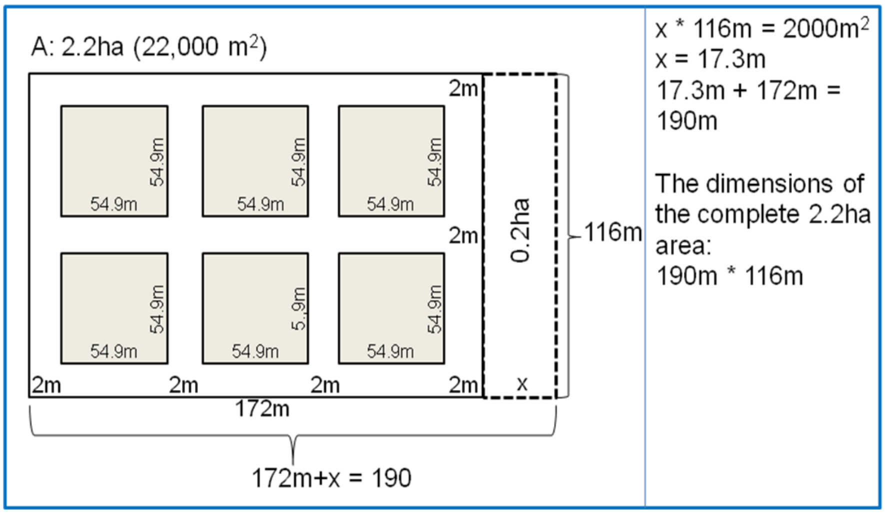
One container:
A: 0.3ha (3010m^2)
V: 603m^3 (603,000L)*

Six containers:
A: 1.8ha (18,000m^2)
V: 3620m^3 (3,620,000L)

*constant value of 0.2m depth

Figure B. Solved dimension for the containers and their area.

The constant area for processing facilities is 0.2 hectares. According to the dimension calculated to containers and safe zone, the dimensions for processing facilities area, are (17.3*116) meters (see Figure C)



x * 116m = 2000m^2
x = 17.3m
17.3m + 172m = 190m

The dimensions of the complete 2.2ha area:
190m * 116m

Figure C. Dimensions for the whole 2.2 ha area.

(3) Biomass productivity in the Worst-case scenario

The harvesting yield: 0.6 g/L/6d * ⅔ = 0.4 g/L/6d
Volume of one container: 603 m^3 (603,000 liters)
0.4 g/L/6d * 603,000 L = 241,000 g/6d (0.241 t/6d)
Six progressed containers = 0.241 t/d
Yield per year: 0.241 t/d * 365d = 88.0 t/a

2.2 hectare area produces 88.0 tons per year.

[2.2 ha = 88.0 t/a] [1.0 ha = x t/a]

2.2x = 88.0

x = 40.0

The biomass productivity in the Worst-case scenario is 40.0 t/ha/a.

(4) Water consumption in the Worst-case scenario

An initial input of water is required when the microalgae cultivation is started for the first time. This is the volume of all six containers:

$603\ m^3 * 6 = 3620\ m^3$ (3,620,000 L)

As microalgae is cultivated in a 1/10 dilution, 362 m^3 of the initial input is raw input and 3000 m^3 is diluted water.

Two thirds of one container volume is removed every day during the harvesting:

$603\ m^3/d * ⅔ = 402\ m^3/d$

This water is circulated back to the system with the portion of raw input:

(x = the added amount of raw input)

$x * 10 = 402\ m^3/d$

$x = 40.2\ m^3/d$

$402m^3/d – 40.2m^3/d = 362m^3/d$

The harvested 402 m^3/d amount of water is replaced with 362 m^3/d of circulated water from the system and 40.2 m^3/d of new raw input.

Raw input: 14700 m^3/a

Evaporation:

Evaporation from a water system can be 2-3 per cent (Kuusisto 2011; Pate 2011). An average of 2.5 per cent evaporation is used in this thesis. Evaporation from six containers:

$(603\ m^3/d * 0.025) * 6 = 90.6\ m^3/d$

This evaporation loss is replaced partly with the excess output from cultivation and new diluted input.

Excess 40.2 m^3/d of water remains after the 362 m^3/d is circulated back to the system for the biomass harvesting.
90.6m^3/d – 40.2m^3/d = 50.4m^3/d
50.4 m^3/d (18400 m^3/a) of diluted input water is needed to fully replace the evaporation. Because of the evaporation replacement, no excess water output comes from the cultivation system.

90.6 m^3/d evaporation by millimeters:
Evaporation from one container is 15.1 m^3/d and the dimensions of one container is (54.9 * 54.9 * 0.2) m = 603 m^3
54.9m * 54.9m * x = 15.1 m^3/d
x = 0,005 m/d (5 mm/d)
1830 mm/a is evaporated.

The ratio between produced biomass and consumed water:
Raw input: [88 t/a = 14700 m^3/a] [1 t/a = x]
88x = 14700
x = 167
Evaporation replacement: [88 t/a = 18400 m^3/d] [1 t/a = x]
x = 209
1 t/a microalgae biomass production requires 167 m^3/a raw input & 209 m^3/a diluted evaporation replacement.

The total water circulation in the system is 180,100 m^3/a (82 % reused dilution water from the system)

(5) Biomass productivity in the Moderate scenario

The harvesting yield: 3.0 * ⅔ = 2.0 g/L/6d
Volume of one container: 603 m^3 (603,000 liters)
2.0 g/L/6d * 603,000 L = 1,206,000 g/6d (1.21 t/6d)
Six progressed containers = 1.21 t/d
Yield per year: 1.21 t/d * 365d = 442 t/a

2.2 hectare area produces 442 tons per year.

[2.2 ha = 442 t/a] [1.0 ha = x t/a]

2.2x = 442

x = 201

The biomass productivity of the Moderate scenario is 201 t/ha/a.

(6) Water consumption in the Moderate scenario.

The ratio between produced biomass and consumed water:

Raw input: [442 t/a = 14700 m^3/a] [1 t/a = x]

442x = 14700

x = 33.3

Water consumption in the Moderate scenario: 1 t/a microalgae biomass = 33.3 m^3/a raw input.

The total water circulation in the system is 147,000 m^3/a (90 % reused dilution water from the system)