BIOMASS AND BIOENERGY 53 (2013) 81–94

Available online at www.sciencedirect.com

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Assessment of a novel alder biorefinery concept to meet demands of economic feasibility, energy production and long term environmental sustainability

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ARTICLE INFO

Article history:
Received 16 June 2012
Received in revised form
4 February 2013
Accepted 7 February 2013
Available online 13 March 2013

Keywords:
Alnus spp.
Biorefinery development
Alder productivity
Renewable energy
Sustainability assessment

ABSTRACT

A biorefinery concept based on alder tree plantations on degenerated soil is developed to comply with indicators of economic feasibility, fossil fuel depletion concerns, and long term sustainability issues. The potential performance of feedstock and biorefinery has been assessed through a literature study and by using a method developed during the study for first hand assessment and comparison of biorefinery system characteristics.

The management of an average alder plantation in a 6-year coppicing system was found to fixate atmospheric nitrogen to the soil in yearly rates between 50 and 200 kg ha^{-1} and produce a 6-year total dry biomass quantity around 33 Mg ha^{-1} plus yearly leaf production. This production could facilitate a biorefinery to serve society with production of energy related and value added products to substitute the use of fossil fuels while at the same time replenishing degenerated soils. Integrating a biomass handling system, an LT-CFB gasifier, a diarylheptanoids production chain, an anaerobic digestion facility, a slow pyrolysis unit, gas upgrading and various system integration units, the biorefinery could obtain the following production characteristics accounted on a yearly basis: Total system Energy Return on energy Invested 2.0, total system Exergy Return on exergy Invested 1.5, Net Energy Output 78 GJ ha^{-1}, Net Exergy Output 50 GJ ha^{-1}, Net carbon sequestration (as CO_2 equivalents) 0.80 Mg ha^{-1}, Total product value 2030 € ha^{-1} and Net Dry Matter Removal of approximately 90%.

1. Introduction

A substantial shift in the energy resources used to fuel societies around the world is in progress due to economic issues, accelerating climate change effects and concerns related to potential fossil fuel depletion [1,2]. An economy based more on bioenergy and other renewable energy types and less on fossil fuels have been suggested numerous times as a way to act on these concerns. The shift from fossil fuels to renewable alternatives is especially relevant within energy production, but also in relation to the production of thousands of other products currently based on petroleum, natural gas, coal etc.

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0961-9534/$ – see front matter
http://dx.doi.org/10.1016/j.biombioe.2013.02.022

To substitute these products with renewable alternatives, the development of new biorefinery concepts is required. The International Energy Agency [3] has defined biorefining as the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials etc.) and bioenergy (biofuels, power and/or heat). Biorefineries are thus developed to produce the same commodities that present day oil refineries produce and some even exceed this product range with new innovative bio-materials, pharmaceuticals, and compounds. These biorefinery concepts should embrace long term sustainability as well as economic feasibility to serve present as well as future generations [4,5].

In addition to the complex combination of economy, sustainability and energy related issues; there is also the issue of land use priority, which is an inevitable topic in all bioenergy related discussions. Land availability is a sensitive and important issue that should be addressed prior to other design related questions.

One way to embrace the issue of land availability is to focus on the use of infertile and marginal lands unsuited for modern agricultural management. Many areas of the world are less fertile today than they were only a few centuries ago due to overexploitation and/or pollution. Overexploitation induces erosion which in turn leads to decreased plant growth and this feedback mechanism slowly reduces soil quality [6]. In the northern part of Europe degraded lands can be found in many places, including 220,000 ha in Estonia, 75% of Iceland, and 100,000 ha in Sweden [6–8].

A biorefinery design which utilizes such soils to substitute the use of fossil fuels while restoring the soil quality simultaneously is desirable. In all the above mentioned locations, local stakeholders have proposed alder tree restoration projects and reforestation initiatives to re-establish soil quality and quantity. Alder trees have also been applied for regenerative purposes on other types of damaged soils e.g. abandoned mine areas [9] and hydrocarbon-contaminated soils [10].

This observation makes the alder a potentially interesting feedstock, and in the present work the outline for a biorefinery concept based on an alder plantation on degraded soil is therefore outlined. The concept will identify and exploit alder species characteristics, biorefinery cascade material use, and synergy effects in the development of an economically feasible, highly productive facility with a high level of long term sustainability.

1.1. About alder

Alder (*alnus*) is the common name of around 34 different species of perennial dicotyledonous trees and shrubs belonging to the *Betulaceae* family. The alders are widespread in temperate, cool and alpine ecosystems on open areas, in forests, in riparian habitats, in mine spoils, in gravel deposits and under wet and cold tundra conditions. The alder are highly resilient with a natural resistance to drought stress, diseases, poor soil and in general alders tolerate a wide range of soils and climates [10]. Furthermore, alder grows rapidly, the litter (the shed leaf material) improves nearby soil properties, new generations re-grow very well when coppiced [11], and seedlings are tolerant to direct sunlight as well as frost [7].

Alder is part of a nitrogen-fixating symbiosis, and can thus prioritize a longer growth season over nutrient retraction. In this way, alders continue their photosynthesis and growth for more than a month after e.g. the basswood photosynthesis has ended [12]. The N-fixation is the result of a symbiosis between the alder and *Frankia* bacteria which form root nodules on the alder roots, and provide atmospheric nitrogen as ammonia to the host plant in exchange for energy [7,10]. The nodules on the alder roots have also been found as host for fungi types increasing the alder's ability to take up water and minerals, such as phosphorous, due to the very large mycelium to root surface ratio [10,13,14]. Through the symbiosis with bacteria and fungi, alder trees contribute positively to the soil quality in their surroundings.

Alder is assessed as biorefinery feed as it is the only native fast growing large tree with nitrogen fixating and deep phosphorus retrieval symbiosis characteristics in the Northern European region and because it has already been proposed for replenishment management of depleted soils in these areas. Another fundamental argument for choosing to assess alder is that it is a perennial crop with little or no fertilization requirements and the harvesting cycles are longer than for non-tree alternatives. Alternative crops would require either intensive fertilization (e.g. willow) and/or intensive, yearly harvesting and management (e.g. clover) and the choice of alder is made to favour sustainability and climate change issues through reduced management and low overall input.

1.2. Goal and scope of the work

The purpose of the present study is to propose, describe, and assess the initial design stages of an innovative and unprecedented biorefinery concept based on alder plantation management on infertile/polluted soils in the Northern Europe region. The biorefinery should have economic potential, be able to substitute products currently based on fossil fuels and at the same time the operation should be characterized by a high degree of long term sustainability and a minimal impact on present land availability.

The study will provide a simple method for assessing the proposed concept from several angles at once and using the results to navigate in a forthcoming development phase. The approach of the study is holistic and aims to combine multiple concerns in a simple development tool. For this reason many details are omitted and simplifications applied. The method is applicable in the initial conception of new biorefinery systems before progressing to a more thorough assessment comprising e.g. practical experiments, classic comparative LCA, economic feasibility studies and detailed process modelling.

This study is divided into 3 parts – 1st, a determination of alder productivity and plantation product characteristics based on available data from literature, 2nd, the development of the biorefinery concept in a number of different system designs, and 3rd, an estimation of key plant parameters within sustainability, energy production and economy, and a relative comparison of these parameters between the different designs. The intended output of the assessment is a simple indication about which of the included system designs – from cradle to gate, best embrace the included palette of impact categories. The structure of the method is illustrated in Fig. 1.

The study is conducted without scale and without unique specifics – e.g. a specific geography. This is proposed as the