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Understanding biorefining efficiency – The case of agrifood waste

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HIGHLIGHTS

- System borders are decisive for biorefining efficiency.
- High exploitation of feedstock potential and substitution efficiency are the keys.
- Nutrient efficiency depends on efficiency of substitution for mineral fertilisers.
- Share of combustion and heat utilisation are decisive for energy efficiency.
- Biorefining increases efficiency in comparison to the current situation.

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ABSTRACT

The aim of this study was to determine biorefining efficiency according to the choices made in the entire value chain. The importance of the share of biomass volume biorefined or products substituted was investigated. Agrifood-waste-based biorefining represented the case. Anticipatory scenarios were designed for contrasting targets and compared with the current situation in two Finnish regions. Biorefining increases nutrient and energy efficiency in comparison with current use of waste. System boundaries decisively influence the relative efficiency of biorefining designs. For nutrient efficiency, full exploitation of biomass potential and anaerobic digestion increase nutrient efficiency, but the main determinant is efficient substitution for mineral fertilisers. For energy efficiency, combustion and location of biorefining close to heat demand are crucial. Regional differences in agricultural structure, the extent of the food industry and population density have a major impact on biorefining. High degrees of exploitation of feedstock potential and substitution efficiency are the keys.

1. Introduction

Biorefining that produces renewable energy (RE) and organic fertilisers from untapped agrifood wastes has the potential to mitigate climate change and eutrophication (Kahiluoto et al., 2011), and to create new business opportunities in rural regions. While rapidly becoming mainstream, little is known about how the value chain should be designed for the potential of biorefining to be best realised. Efficiency is an important feature of sustainable biorefining (Kokossis and Yang, 2010), nutrient, carbon (C) and energy efficiency being key to both environmental and economic performance. Efficiency is, however, multifaceted. It can crucially mislead decision-making if its dependence on the choices along the entire biorefining supply and demand chain is not revealed.

Currently inefficiently utilised agrifood waste and by-products of primary production, food industry, retail and consumption have great potential as nutrient, C and energy sources (Kahiluoto et al., 2011). They can help mitigate climate change and eutrophication through substituting for non-renewable energy (non-RE) and fertilisers or sequestering C in soil. The products either substitute for imported fuels and fertilisers or represent new exports and provide jobs and finance for public services (Bailey et al., 2011), thus fostering regional economies. In modern agrifood-waste-based biorefining it is possible to integrate all these benefits, if in addition to energy or C, nutrients in biomass are also utilised. The best design of the supply and demand chain depends on benefit prioritisation.

Choices for every step from biomass supply (types and quantity covered), collection and conversion (processes, location), to markets (distribution, energy consumption, fields) and demand substituted for (energy, fertilisers) may affect the overall efficiency of

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biorefining. Due to high costs of biomass transportation, biorefining is typically organised on a local or regional scale. Therefore, regional conditions may affect the appropriate design and efficiency of biorefinery systems (Kahiluoto et al., 2011; Kokossis and Yang, 2010). The relevant part of the value chain varies depending on the question and the primary beneficiary or decision-maker posing it.

Biorefining is increasingly promoted and shaped by public incentives (e.g. Law of the operating aid for renewable electricity in Finland 1396/2010, Supplementary Information (SI)) and developed by pioneering entrepreneurs. These activities are based on intuitive assumptions rather than on systematic comparisons of biorefinery systems. Despite the policy priority on material use prior to energy use (Directive 2008/98/EC), the studies of material efficiency of agrifood-waste-based biorefining (e.g. Cui et al., 2012; Karp et al., 2011; Leung et al., 2012; Martínez Sabajanes et al., 2012) are in the minority and only few studies of nutrient and C exploitation (Anex et al., 2007; Cayuela et al., 2010) have been conducted. Energy efficiency of feedstock transportation and conversion, and utilisation of products, has been addressed (e.g. Chen et al., 2012; Laser et al., 2009; Pöschl et al., 2010) and a systems approach has been suggested to be applied in development of biorefining (Kokossis and Yang, 2010). However, no comparison of contrasting biorefinery systems covering the entire value chain, i.e. all the system levels (Bunge, 1985) of biorefining, has been previously performed. This study appears to be the first to reveal the dependence of efficiency estimates on the system boundaries set in the supply and demand chain of biorefining.

The aim of this study was to assess nutrient, C and energy efficiencies of contrasting agrifood-waste-based biorefinery systems, focusing on several system levels. The biorefinery systems considered form coherent scenarios, each based on a distinct design target. The targets were set to (1) mitigate climate change; (2) mitigate eutrophication or (3) enhance the regional economy. The biorefinery scenarios were developed for two contrasting case regions in Finland.

The following research questions were asked:

1. What are nutrient (N, P), carbon (C) and energy efficiencies of agrifood-waste-based biorefining?
2. What are the main determinants of efficiencies that depend on regional conditions and the design of biorefinery systems?
3. How do the efficiencies depend on whether only biorefinery plants or entire supply and demand chains of the biorefinery products are taken into account?

2. Methods

2.1. Contrasting biorefinery scenarios

Agrifood-waste-based biorefinery scenarios were designed for contrasting targets. The targets and system boundaries were identified in workshops in discussion with actors representing agrifood and biorefinery systems. The first scenario was designed to mitigate climate change by substituting for non-RE (ENERGY). The second scenario was designed to mitigate eutrophication (WATER) and the third one to enhance the regional economy (ECONOMY). The current situation was described by a baseline scenario (PRESENT). The scenarios comprised several system levels (Fig. SI1): Biorefinery plants level, including conversion within the biorefinery plants; biorefinery chains level, including also transportation, and biorefinery region level, including also the supply of the biomass potential and the demand for the fertilisers and energy, including locations, and the estimated substitution of mineral fertilisers and non-RE products, based on the data for the case region. The main features of the scenarios and differences based on the design targets were defined at various system levels, for the aspects (Table 1) having a hypothetical impact on the studied efficiencies. The anticipatory scenarios (Verburg et al., 2006) generated were coherent story lines; all choices (Table 1) were made based on the design target of the scenario. However, a small loss in the target was accepted if substantial benefit for another target was achieved. Conversion processes were chosen so that both nutrients and energy were recoverable in all the three scenarios. Therefore, anaerobic digestion (AD) was a key technology. The sensitivity of the design target of climate change mitigation was analysed through examining another climate change mitigation scenario also designed for recycling and sequestering C (CARBON) (Table SI1) rather than replacing non-RE (ENERGY). The sensitivity of the design target for the choice of the conversion process was analysed in ENERGY.

The biorefinery scenarios were formed based on the biomass potential (Table 2) of agrifood wastes and by-products currently available, and within the next 5 years through implementation of the policy targets and regulations already set (see the more detailed biomass assessment in Kahiluoto et al. (2011)). The heating values (LHV_d) of the biomass types were based on figures reported in the literature (Mattsson Petersen et al., 2005; Phyllis, 2012). The scenarios were developed for two case regions, for rural South Savo in eastern Finland and for more densely populated Satakunta in south-western Finland (Table SI2). The fresh-weight based density of concentrated biomass was 2.4 t km^{-2} (tonnes per square kilometre) in South Savo and 35 t km^{-2} in Satakunta and scattered biomass 37 t km^{-2} and 115 t km^{-2}, respectively. In Satakunta the share of feedstock in ENERGY and ECONOMY, and the energy demand of transportation activities were extrapolated based on the data for South Savo (see detailed below).

Feedstock types and quantities for biorefinery plants (Table 3; see CARBON Table SI3) was defined taking into account the design targets (Table 1) and the location of the biomass. Additionally, unprocessed biomass (Table 1, manure) is a part of utilised biomass in PRESENT because it is currently applied in agriculture. In South Savo, the content of N in feedstock is then 3.4 kt a^{-1} and in material products 3.2 kt a^{-1}, P 0.9 kt a^{-1} and 0.9 kt a^{-1}, and C 56 kt a^{-1} and 54 kt a^{-1}, respectively (cf. Table 3). In Satakunta, the content of N in feedstock is 8.1 kt a^{-1} and in material products 5.4 kt a^{-1}, P 2.1 kt a^{-1} and 1.7 kt a^{-1}, and C 130 kt a^{-1} and 120 kt a^{-1}, respectively. Feedstock is agrifood waste and by-product biomass, and therefore production of the main products of the agrifood system, i.e. food, feed, fuel and fibre, is excluded from the scenarios. All harvesting, collecting and transporting of feedstock, and transporting, spreading and application of material products (organic fertilisers), are included.

The location of the biorefinery plants and the collection areas of the feedstock (Table 1, Fig. SI2; see CARBON Table SI1) were defined in South Savo based on the location of biomass, animal farms (SI Evira, 2007), district heating networks (SI Energiateollisuus, 2008) and the street and road network (Digiroad, 2009). ArcGIS software and Network Analyst were used to define the collection areas (ESRI, 2010). If the whole biomass potential was not biorefined, as a consequence of the design target, the remaining biomass was included in the scenario and treated as in PRESENT (feedstock for biorefining or utilised as unprocessed biomass); the share of such biomass ranged from 1.2% to 32% (Table 1).

In Satakunta, in ENERGY and ECONOMY, the share of feedstock of the biomass potential was estimated based on the district heat demand. First, (Eq. (1)), the heat demand in ENERGY in Satakunta was estimated based on the heat production (supply) in ENERGY in South Savo and the densities and the shares of the biomass: