Development of life cycle assessment for residue-based bioenergy

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Summary

An optimistic estimate suggested that, by 2050, bioenergy could sustainably contribute up to one third of the global primary energy supply from the current state of approximately only ten percent. More specifically, residue-based bioenergy is speculated to increase its key role in the future energy mix as a consequence of the harsh competition between food and energy sectors over the same raw materials (sugar, starch, and vegetable oil). This competition has encouraged the exploitation of non-food resources which are so far still dominated by fuel wood for traditional cooking. This fact demonstrates that there continues to be significant opportunities for improved utilization for bioenergy that is more efficient and environmentally friendly. This trend would likely be enhanced by the advancement in research and development on emerging conversion technology such as second-generation bioethanol. In line with this trend, potential biomass residues as bioenergy feedstock are abundant and available in many different regions worldwide. The global production of just crop residue can reach 3.8 billion metric tons annually, which is equivalent to a total energy of 70 EJ. These resources, however, must be diligently managed since, in addition to bioenergy, biomass residues also play many other competing roles. In particular, residues generated in fields naturally contribute to maintaining soil fertility and future harvests. Meanwhile, those generated in post-harvest facilities may also be used as fertilizers, feed, fibers, or other biorefinery feedstocks.

The overall framework of this thesis is to develop an approach to compare the impacts between leaving biomass residues in fields and utilizing them for bioenergy. In that regard, the objectives of this thesis are to identify the key issues when conducting a life cycle assessment (LCA) of residue-based bioenergy and to propose improvement in LCA procedures, specifically in the areas of life cycle inventory (LCI), life cycle impact assessment (LCIA), and methodological choices in the comparative LCA. It was discovered that the key issues associated with residue-based bioenergy relate to four primary characteristics with respect to its raw materials (biomass residues), i.e., excessive removal from plantation fields which can affect soil fertility; valuation (relative to biomass products); competing uses (bioenergy, feed, fiber, fertilizers); and treatment of biogenic carbon (assumptions of carbon neutrality vs. complete inventory). These unique features require specific LCA approaches which vary from those of conventional product-based bioenergy. These approaches include: [1] solutions to the existing dissimilar practices in the LCI of biogenic carbon; [2] an LCIA method of removing biomass residues from soil on biomass productivity; and [3] methodological choices in comparative LCA of biomass residues utilization.

To accomplish the above objectives, five research questions are discussed and answered in Chapters 2 to 6. In Chapter 2, the key issues in conducting an LCA of bioenergy systems are identified. Goal and scope definition is an important initial step since the choice of methodology used depends on the purpose of an individual study. These methodological choices include system boundary, functional unit, inventory data, and treatment of multi-functional processes (allocation). Within this category, there is also a debate between attributional and consequential LCA which, for bioenergy, is even more crucial than for ordinary products.

Bioenergy poses more methodological challenges than other types of renewable energy since the system boundary also incorporates agricultural phases to produce biomass feedstock. In this aspect, there is a question of how to properly treat biogenic carbon in terms of capture and emission flows in the inventory. In addition, agricultural processes lie in the intersection between environmental and economic systems. Meanwhile, LCA methodology has not been particularly unambiguous with regard to direct and indirect land-use changes, regional variability leading to regionalized impact assessment, and the choice of impact

categories. These are challenges for further development of an LCA in order to improve analyzing a bioenergy system.

In Chapter 3, the environmental sustainability status of second generation bioethanol is evaluated. Despite the non-homogeneous system definition of the reviewed LCA studies, it was concluded that second generation bioethanol exhibits improved performances over fossil fuel for, at least, the two most studied sustainability aspects, i.e., net energy output and global warming. For the latter parameter, carbon sequestration at the biomass generation stage can consistently offset total GHG emissions from all elements of the life cycle chains at high ethanol percentage (≥85%).

The aspects of biogenic carbon and agrochemical input for energy crops and biomass residues and the effect of the removal of the latter from soil have not been addressed consistently. The bioethanol conversion process is primarily based on simultaneous saccharification and co-fermentation which is characterized by high yield and low energy input. In this regard, the LCA results tend to under estimate the actual impacts of current technology. The choice of allocation methods strongly influences the final results, particularly when economic value is employed as a reference. Substitution of avoided burden appears to be the most popular allocation method in practice, followed by partition based on mass, energy, and economic values.

In Chapter 4, the assumption of biogenic carbon neutrality is evaluated. This study demonstrates that the global warming impacts of scenarios based on the LCA principles, treating all relevant input-outputs as genuine flows (including biogenic carbon), provides various results which are in many cases different from those assuming biogenic carbon neutrality (excluding biogenic carbon). In addition to the existing arguments of carbon stock change and carbon storage capacities of long-rotation trees or wood products, the current study supports the assertion that the assumption on biogenic carbon neutrality introduces biases to the ‘true’ values based on a complete inventory. The extent of such a bias, which can make the values of global warming impacts substantially higher or lower, depends on specific situations. Three factors are identified to substantially propagate biases in the evaluation of global warming performances of a bioenergy system. They are differences in framing system boundaries (cradle to grave vs. cradle to gate), forms of carbon emissions (CO_2 vs. CH_4), and valuation of biogenic carbon (biomass products vs. biomass residues). The results of this study are expected to contribute to the harmonization of future bioenergy LCA by directing further research to adopt more the concept of utilizing a complete inventory rather than the neutrality assumption.

In Chapter 5, the impact of removing biomass residues from soil on biomass productivity is modeled. An impact assessment method relating the removal of biomass residues with soil organic carbon and net primary production has been developed. The assessment method was developed within the LCA framework based on a specific system definition, i.e., decomposed biomass residues above soil surfaces resulted in net carbon flow into soil compartments. In addition to GHG emissions into the atmosphere, the soil organic carbon functions as an additional elementary flow to complete the overall carbon balance. The assessment method considers the effects of soil organic carbon on soil biomass productivity as a midpoint indicator, which is expressed as a loss of net primary production. The impact assessment method is in accordance with the ISO-standard format, comprising a characterization factor and an input term representing changes in elementary flows:

$$\left(\Delta\mathrm{NPP}\right)_{\%\mathrm{Removal}} = \left(\frac{\mathrm{dNPP}}{\mathrm{dSOC}}\right)_{\mathrm{Climate,\,Vegetation\,,Soil}} \times \frac{\mathrm{dSOC}}{\mathrm{d\%Removal}} \times \%\mathrm{Removal}$$

where NPP is the net primary production in g-carbon/(m^2.year) and SOC is the soil organic carbon in g-carbon/m^2.

The operation of the proposed method was illustrated with a moderate case study. It demonstrated that the method has genuine potential to be developed as metrics for assessing the sustainability of bioenergy systems. However, to operate the assessment model for a specific region, data for spatially detailed implementation within bioenergy systems in various regions need to be completed.

In Chapter 6, the methodological choices on how to compare the impact of various treatment options on biomass residues in a palm oil system are proposed. Guidelines for methodological choices in terms of system boundary, functional unit, and solutions to multi-functional problems have been proposed. The methods can be employed to systematically compare the LCA results of different treatment options and valuation of empty fruit bunches (EFB) in a palm oil system. Comparison based on the same multi-functional units can be accomplished only in cases where additional co-products were utilized internally. Based on a global warming impact, the mulch option was preferred among other treatments (compost, ethanol, treated in incinerator, and sold as coproducts). This conclusion requires further verification since results are extensively dependent on local inventory data. The effect of the avoided process of producing synthetic fertilizers and the assumption that all parts of mulch are available as soil nutrient dominantly determined the final result. The study also demonstrates that the status of EFB as waste or goods is influential on the final results if the EFB is employed externally but has no effect if it is utilized internally.

Knowledge regarding preferred alternatives for managing biomass residues like EFB could improve environmental performances and orient towards best practices. Further studies incorporating a site-specific case of palm oil systems would better illustrate the usefulness of the proposed guidelines. Besides palm oil systems, the approach is also readily applicable to biomass residues in other agro-based industrial systems.