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Review

Emerging role of Geographical Information System (GIS), Life Cycle Assessment (LCA) and spatial LCA (GIS-LCA) in sustainable bioenergy planning

Moonmoon Hiloidhari [a], D.C. Baruah [b], Anoop Singh [c], Sampriti Kataki [b], Kristina Medhi [a], Shilpi Kumari [d], T.V. Ramachandra [e], B.M. Jenkins [f], Indu Shekhar Thakur [a,]*

[a] *School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110067, India*
[b] *Department of Energy, Tezpur University, Tezpur 784028, Assam, India*
[c] *Department of Scientific and Industrial Research, Ministry of Science and Technology, Government of India, New Delhi 110016, India*
[d] *Centre for Energy Studies, Indian Institute of Technology Delhi, New Delhi 110016, India*
[e] *Energy and Wetland Research Group, Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560012, India*
[f] *Department of Biological and Agricultural Engineering, University of California Davis, California 95616, USA*

HIGHLIGHTS

- GIS, LCA & spatial LCA application in bioenergy are of increasing importance.
- Resource assessment, logistic planning, plant design could be optimized using GIS.
- Bioenergy system with better environmental performance can be designed using LCA.
- Uncertainties in LCA must be addressed for its better applicability in bioenergy.
- Spatial environmental impacts of bioenergy could be addressed using spatial LCA.

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ABSTRACT

Sustainability of a bioenergy project depends on precise assessment of biomass resource, planning of cost-effective logistics and evaluation of possible environmental implications. In this context, this paper reviews the role and applications of geo-spatial tool such as Geographical Information System (GIS) for precise agro-residue resource assessment, biomass logistic and power plant design. Further, application of Life Cycle Assessment (LCA) in understanding the potential impact of agro-residue bioenergy generation on different ecosystem services has also been reviewed and limitations associated with LCA variability and uncertainty were discussed. Usefulness of integration of GIS into LCA (i.e. spatial LCA) to overcome the limitations of conventional LCA and to produce a holistic evaluation of the environmental benefits and concerns of bioenergy is also reviewed. Application of GIS, LCA and spatial LCA can help alleviate the challenges faced by ambitious bioenergy projects by addressing both economics and environmental goals.

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* Corresponding author.
E-mail addresses: hiloidhari@gmail.com (M. Hiloidhari), baruahd@tezu.ernet.in (D.C. Baruah), apsinghenv@gmail.com (A. Singh), sam.kataki@gmail.com (S. Kataki), kristi0310@gmail.com (K. Medhi), shilpidas.iit@gmail.com (S. Kumari), cestvr@ces.iisc.ernet.in (T.V. Ramachandra), bmjenkins@ucdavis.edu (B.M. Jenkins), isthakur@hotmail.com (I.S. Thakur).

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1. Introduction

The International Renewable Energy Agency (IRENA) indicates that by 2030 biomass would comprise 20% of the global primary energy supply, doubling its share from 10% in 2010 (IRENA, 2015). The prospect of agro-residue as prominent global bioenergy provider is also very high in the near future. Global agro-residue availability is estimated to be 3.6–17.2 billion tonnes with an equivalent energy potential of 13.1–122 EJ (WBA, 2015). Some distinct advantages of agro-residue as energy source are: (i) suitable feedstock for heat and power and transportation fuel production, (ii) generation of wide range of by-products with potential for further valorization through the biorefinery process, (iii) a carbon neutral or low carbon fuel that emits less carbon dioxide than fossil fuels in its life cycle, (iv) scope for development of bioenergy based entrepreneurial activities, (v) feasibility of generating decentralized mode of energy to empower remote areas.

Agro-residues are geographically distributed with variation in spatio-temporal availability. For viable commissioning of biomass power plant, prior and precise database of residue distribution, seasonal fluctuation (peak and lean period of availability) is a pre-requisite. Logistics such as residue harvest, collection, storage, transportation are spatially interlinked and need meticulous planning. Adequacy, precision, reliability of data collected through traditional methods (survey or secondary data collection) for bioenergy planning is a matter of question, which often lead to over or under estimation of potentially accessible energy source. Therefore, energy and environmental assessment need decision support system (DSS) for effective planning (Sacchelli et al., 2013). Spatial tools are able to relate large scale environmental assessment with medium and small scale DSS, useful for decision makers. Geographical Information System (GIS) is an important decision making spatial tool which aids precise assessment of distributed renewable energy resources (Yue and Wang, 2006; Angelis-Dimakis et al., 2011; Ramachandra et al., 2005). Review of the potential applications of GIS in agro-residue bioenergy planning is one of the objectives of this paper.

The climate change mitigation benefit of bioenergy has become a much debatable issue in recent times because of the limited information on the direct and indirect environmental consequences of bioenergy. It is expressed that unsustainable production or over-exploitation of bioenergy feedstock may exacerbate greenhouse gas emissions and jeopardize many ecosystem services (Fargione et al., 2008; Searchinger et al., 2008; Danielsen et al., 2009; Lapola et al., 2010; Liska et al., 2014). Large scale cultivation of bioenergy crops can lead to the so-called food *vs.* fuel debate (Tilman et al., 2009). Loss of carbon pools and carbon sequestration dynamics may occur from the conversion of land to bioenergy cropland, which can only be balanced by bioenergy crops in hundreds of years (Gibbs et al., 2008). In this regard, Life Cycle Assessment (LCA) based investigation of possible environmental implications of bioenergy production is critical to avoid decline of existing carbon stocks (Cherubini et al., 2009). A review of the applications of LCA in agro-residue bioenergy is another objective of this paper.

GIS and LCA differs from each other in the sense that, the former is used for spatial data acquisition, storage, processing and visualization, while LCA is not, but they are complementary to each other (Gorniak-Zimroz and Pactwa, 2015). Certain impacts of bioenergy (*e.g.* impact on biodiversity) are spatially allocated due to the distributed nature of biomass feedstocks. Current LCA measures are inadequate to spatially account such impacts. The integrated use of GIS and LCA (hereafter termed as spatial LCA) could address such issues by allocating the impacts into spatial units (Bengtsson et al., 1998; Geyer et al., 2010; Gasol et al., 2011; Gorniak-Zimroz and Pactwa, 2015). Spatial LCA is an emerging research field and the discussion of current development in this field is also one of the objectives of the paper.

In line with the above discussion, the present paper reviews the potential applications of GIS, LCA and spatial LCA in sustainable planning of residue-based bioenergy program. The review includes a discussion on the role of GIS in biomass resource assessment, biomass logistics planning and bioenergy power plant design. The review also highlights the application of LCA in evaluation of environmental performance of agro-residue bioenergy systems. The uncertainties associated with LCA study and measures to address them are also reviewed. Further, the importance and potential benefits of integrating GIS into LCA platform (spatial LCA) for bioenergy planning are also reviewed. It is expected that, analysis of the aspects about the significance and practical relevance of GIS, LCA and spatial LCA tool covered in this study will be helpful in making informed decisions about future directions for bioenergy planning, research and development.

2. Application of GIS in agro-residue bioenergy planning

The whole supply chain of a bioenergy project can be divided into three major spatially interlinked elements: (i) resource assessment, (ii) logistic planning, and (iii) power plant design. GIS intervention in bioenergy planning is necessary because: (i) diverse varieties of agro-residues are used as energy feedstock, therefore maintaining their spatio-temporal database concerning physico-chemical characteristics, availability and distribution is important. GIS helps in managing such database which later can guide the industries for effective collection of raw material, allocation of the benefits of bioenergy and cost-benefits analysis (Long et al., 2013; Alfonso et al., 2009). Periodic updating of the biomass inventories is also necessary to assess future feedstock supply potential; (ii) ensuring sustained feedstock supply is critical for viable commissioning of a power plant. Prior knowledge of any fluctuation in feedstock supply would allow the user to make necessary arrangement for alternative feedstock supply during lean period of supply and it can be indicated through GIS (Stephen et al., 2010); (iii) consideration of the environmental requirement of residue and harvest constraints, economy, technology, competing uses of residue, local socio-political dynamic, land use, logistic facilities, civil and industrial users can also be assessed with GIS (Alfonso et al., 2009; Beccali et al., 2009; Gomez et al., 2010; Jiang et al., 2012).

The uneven geographical distribution of agro-residue demands proper logistic planning for the collection and transfer of residue in a time and cost-efficient manner. The various parties involved in the biomass supply chain that influence the final bioenergy cost include the supplier of biomass, transportation and distribution entities, energy production facility developers and operators, government and utility firms and the end users (Mafakheri and Nasiri,

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2014). The implementation of a spatial network can help the parties involved in bioenergy planning to act in a common framework by sharing costs, logistics, and personnel (Beccali et al., 2009). The rising competition for production areas, raw materials and infrastructure also demands spatially explicit logistic planning (Fiedler et al., 2007).

Among the logistic parameters, transportation can be cost intensive depending upon the distance and mode of transport (railway, roadway, waterway), nature of the feedstock (loose or dense) and the condition of the transport route. Optimization of the transportation network can significantly reduce the cost of transport. GIS has the capability to model least-cost transport pathway (Perpina et al., 2009; Ebadian et al., 2011; Jiang et al., 2012; Hiloidhari et al., 2012). For example, Network Analyst extension of ArcGIS software can model least-cost transport pathway for delivering biomass feedstock from source to user location. It allows one to perform multiple network-based spatial functions such as identification of optimal/shortest route, closest facility, service area, origin-destination analysis (Perpina et al., 2009). Further, transporting compacted (baled) biomass reduces cost and CO_2 emission, even for short distances by allowing higher amount to be carried (Alfonso et al., 2009).

Another logistic parameter that requires managerial attention is the selection of optimal biomass collection area and power plant site, where multiple factors come into play. Selecting optimal biomass collection areas should be in accordance with existing agricultural, geographical and infrastructural characteristics of the area encompassing supply and user locations (Beccali et al., 2009). The site should be easily accessible by transport route, near to utility points, feasible for the optimum planning of power transmission lines (Zubaryeva et al., 2012). Further, the plant should be installed in reasonable distance from residential areas, nature reserves to minimize potential negative impacts of plant operation and waste disposal. Beccali et al. (2009) developed a GIS method to assess the techno-economic potential of biomass for energy generation in Sicily through identification of efficient transportation network and optimal biomass collection areas. Similarly, Fiedler et al. (2007) designed a GIS logistic model for cost efficient supply of biomass feedstock to industrial units by analyzing the profitability of investment in infrastructure and equipment for biomass supply.

GIS based biomass power plant site selection can be done through two methods: (i) suitability analysis (ii) optimally analysis as elaborated by Shi et al. (2008). Suitability analysis allows user to identify the most suitable site for a power plant among many candidate sites, based on user defined constrain and supportive criteria. On the other hand, optimally analysis considers the relationship between biomass and power plants in order to find the optimal power plant locations at minimum transportation cost. The optimization of biomass power plant location could be done either through location-allocation modelling or supply-area modelling. Using the optimally analysis approach, Shi et al. (2008) identified potential sites for biomass power plants in Guangdong Province, China, considering the cost of transportation as a prime determining factor in developing bioenergy plant.

Logistic planning for biomass collection can be further influenced by the type of land holding. For example, in India and China, due to small agricultural landholding by the farmer, collecting agro-residue biomass from farmland may be complicated compared to the Western countries (Yu et al., 2012). For the same collection radius, the collectors have to deal with a larger number of farmers, with organized logistic of contracting, collection and transportation (Yu et al., 2012). In a long supply chain, distributed biomass receiving stations (satellite storage) must be optimized for least cost delivery of biomass as reported by Yu et al. (2012). However, Gomez et al. (2010) reported that, the size of a collection area produces two counteracting effects on the final cost of energy generated. A large biomass collection area results in higher power plant capacity, making the power plant economically reliable, but, it increases the transportation costs of the biomass to the plant. Therefore, the authors (Gomez et al., 2010) have suggested that, in a large scale study with large geographical biomass supply area (e.g. country, province), it is impractical to optimize the size and location of every possible plant. But the better option is to use the same collection area for the whole of the territory and size of this area is to be determined in a way to fulfil the individual plant's minimum installed capacity (Gomez et al., 2010).

Egbendewe-Mondzozo et al. (2011) proposed a spatial bioeconomic model, an integration of biophysical -GIS- economic regional mathematical optimization model to estimate biomass supply from cellulosic crops and crop residues. The GIS part provides the transportation parameters to the bioeconomic model. Overall, the model can predict how biomass supply and environmental consequences respond to changes in genetic and biological management as well as market prices and government policy. Similarly, J. Singh et al. (2011) developed a GIS model for agro-residue based decentralized biomass power plant design at development block level in Punjab, India, which can be useful to decide optimum power plant locations with minimum storage and handling cost of feedstocks. GIS application has also been found suitable for village level small scale energy planning (Hiloidhari and Baruah, 2011; Kaundinya et al., 2013). Table 1 summarizes selected numbers of recent GIS based bioenergy study.

Table 1
Some examples of GIS applications in agro-residue bioenergy planning

Reference	Remarks
Höhn et al. (2014)	GIS methodology for biomass transport optimization
Lin et al. (2013)	GIS based biomass supply chain optimization model (BioScope)
Monforti et al. (2013)	GIS based assessment of agro-residue bioenergy production in the European Union
Herr and Dunlop (2011)	R statistical software and GIS for mapping of biomass feedstock density and concentration
Messineo et al. (2012)	GIS base assessment of power plant economic viability
Hua et al. (2013)	GIS based analysis of the geospatial relationships between rice farms and power plants
Kurka et al. (2012)	GIS model to identify suitable locations of CHP bioenergy plants in Scotland
Zubaryeva et al. (2012)	Analytic hierarchy process (AHP) combined with GIS to develop territorial information system for biogas planning
Kuzevičová et al. (2013)	Assessment of agro-forestry bioenergy potential in Slovakia using Corine Land Cover data and GIS
Sultana and Kumar (2012)	GIS based location-allocation approach for techno-economic evaluation of bioenergy facility
Lourinho and Brito (2015)	GIS based method to estimate technical potential of agro-forestry biomass in Portugal
Tiba et al. (2010)	GIS platform for management and planning of solar, biomass and wind energy in rural Brazil
Garcia et al. (2015)	GIS based study to analyze agro-forestry biomass availability and transport logistics
Haase et al. (2016)	GIS based assessment of sustainable crop residue potentials in five European regions
Malico et al. (2016)	Assessment of biomass availability, techno-economic feasibility and environmental aspects of utilizing agro-forestry residues using GIS and RETScreen

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3. Issues needing attention while using GIS for bioenergy planning

Some issues that could impact the quality of the GIS outputs are discussed below:

(i) Pre and post -GIS analysis field visits to random sample areas are important to ascertain the accuracy of the GIS mapping. Systemic accuracy assessment using standard methods such as computation of error matrix (also called as confusion matrix) can increase the preciseness of the GIS output. Bioenergy planning which involves land use land cover mapping, the minimum mapping accuracy should be 85% (Foody, 2002).

(ii) The usefulness of the GIS output is influenced by the quality of satellite/digital image used for analysis. For example, good quality land use land cover map can be generated using medium resolution image (e.g. LISS-III satellite image of 23.5 meter spatial resolution). However, to map cost-efficient road network for biomass transportation, high resolution image is necessary (e.g. LISS-IV image of 5.8 meter spatial resolution) to extract all the details of the major and minor roads of a study area.

(iii) Precise image processing in terms of georeferencing, radiometric calibration, noise removal, image enhancement, post-classification smoothening are other necessary requirements to achieve higher mapping accuracy.

(iv) The choice of image classification method (manual *vs.* digital) can also influence the quality of the GIS products.

Therefore, careful consideration of the above points prior to initiating the GIS mapping is essential for precise bioenergy planning.

4. Life Cycle Assessment (LCA) in agro-residue bioenergy

Considering the environmental uncertainties associated with bioenergy production as discussed in the Introduction part, it is imperative to analyze the pros and cons of bioenergy generation from a Life Cycle Assessment (LCA) prospective. The LCA is a tool to define the environmental burdens from a product, process or activity by identifying and quantifying energy and materials usage, as well as waste discharges, assessing the impacts of these wastes on the environment and it also evaluates the opportunities for environmental improvements over the whole life cycle (Singh and Olsen, 2012). LCA also helps streamline the production process by suggesting the best alternatives to minimize the overall environmental impact. There are four main steps in LCA study: (a) goal and scope definition, where the goal and scope of the study, system boundary, functional unit are identified and defined, (b) life cycle inventory (LCI), life cycle of the product under study is modelled considering all the inputs and outputs; (c) life cycle inventory analysis (LCIA), where the environmental relevance of all the inputs and outputs of a product is assessed, and, (d) Interpretation, the results of the study are reported and possible measures to reduce burden on the environment is suggested at this stage. The various phases of LCA study are shown in Fig. 1 (Rathore et al., 2013). So, LCA is basically a systematic study of a product's life cycle, primarily aiming at reducing its environmental burden (in other words increasing the product's environmental acceptability).

In any bioenergy production system, the farming stage results in significant GHGs emissions and other environmental impacts due to the use of energy intensive farm machinery for irrigation, land preparation, sowing, harvest, collection and transportation of feedstock. Production and application of synthetic fertilizer and pesticide also lead to emissions and impacts soil and water quality. It is reported that, in case of sugarcane-based bioenergy generation, the farming stage has the highest environmental impacts due to land use, fuel and agro-chemicals consumption (Contreras et al., 2009). Sugarcane bagasse can be used for production of both bioelectricity and bioethanol. Lower energy related emissions could be achieved if bagasse is used for co-generation based electricity compared to bagasse bioethanol or fossil energy system (Botha and von Blottnitz, 2006; Ramjeawon, 2008). Further, integrated production of first generation (1G) and second generation (2G) bagasse bioethanol has been proposed as an environmentally better option than 1G conventional production process (Gnansounou et al., 2015). In a comparative *cradle-to-gate* LCA of sugarcane bioethanol production in India and Brazil, Tsiropoulos et al. (2014) observed that Indian bioethanol causes lower or equal GHGs emissions, non-renewable energy use, human health impacts and ecosystem impairment compared to Brazilian bioethanol. The possible reason for such lower emissions is that the Indian bioethanol program is largely based on sugarcane molasses, a by-product of sugar production system, resulting in the allocation of environmental burden between product (sugar) and by-product (molasses). The *cradle-to-gate* LCA is a partial LCA from resource extraction (cradle) to factory gate (gate). On the other hand, the *cradle-to-grave* is the full LCA from resource extraction (cradle) to waste disposal (grave).

LCA studies have also demonstrated the environmental benefits of rice and corn residue based bioenergy production (Shafie et al., 2014; Sanscartier et al., 2014; Nguyen et al., 2013; Soam et al., 2017). Soam et al. (2017) reported that electricity production from rice straw produces a higher GHGs emissions reduction compared to biogas production in Indian condition. In Malaysia also, rice straw based power generation was indicated to emit less GHGs in comparison with coal or natural gas (Shafie et al., 2014). However, according to Silalertruksa and Gheewala (2013), bioethanol production from rice straw results in higher environmental benefit compared to combustion-based power production or thermo-chemical conversion of straw to Biomass-Dimethyl Ether (bio-DME). On the other hand, according to Tonini et al. (2016), biofuel production from agro-residues without involving land use change is a promising emissions reduction option, but the feed-sector's annual crops or residues should not be used to produce biofuel, as land use change related GHGs emissions exceeds any GHGs savings from displacing conventional energy sources. Using corn cob as fuel pellets for electricity generation, a 40% and 80% reduction in GHGs emissions compared to coal and natural gas combined cycle (NGCC) has been reported by Sanscartier et al. (2014). LCA study also finds that co-firing of biomass with coal results in substantial emissions reduction (Sebastián et al., 2011). However, the quantity of emissions reduction will depend upon the degree of biomass pre-treatment and coal boiler efficiency and hence the use biomass with low pre-treatment and with minimum effect on boiler efficiency is suggested to maximize emissions reduction (Sebastián et al., 2011). Furthermore, the size and design parameters of biomass power plant also influence the emission pattern. Butnar et al. (2010) reported that, biomass power plant with generation capacity in the range of 10–25 MW yield better environmental performance, since for bigger power plant (>25 MW), the higher efficiency of electricity production is overtaken by the higher biomass transport distance and constraints of land availability for biomass cultivation. A. Singh et al. (2011), through a LCA study reported that the type of biogas reactor has an influence on emissions savings by up to 15%. Although the use of biomass (such as wheat straw, poplar and Ethiopian mustard) as a substitute to coal or natural gas reduces global warming, non-renewable energy use, human toxicity and eco-toxicity, however, it also leads to increased risk of eutrophication, photochemical

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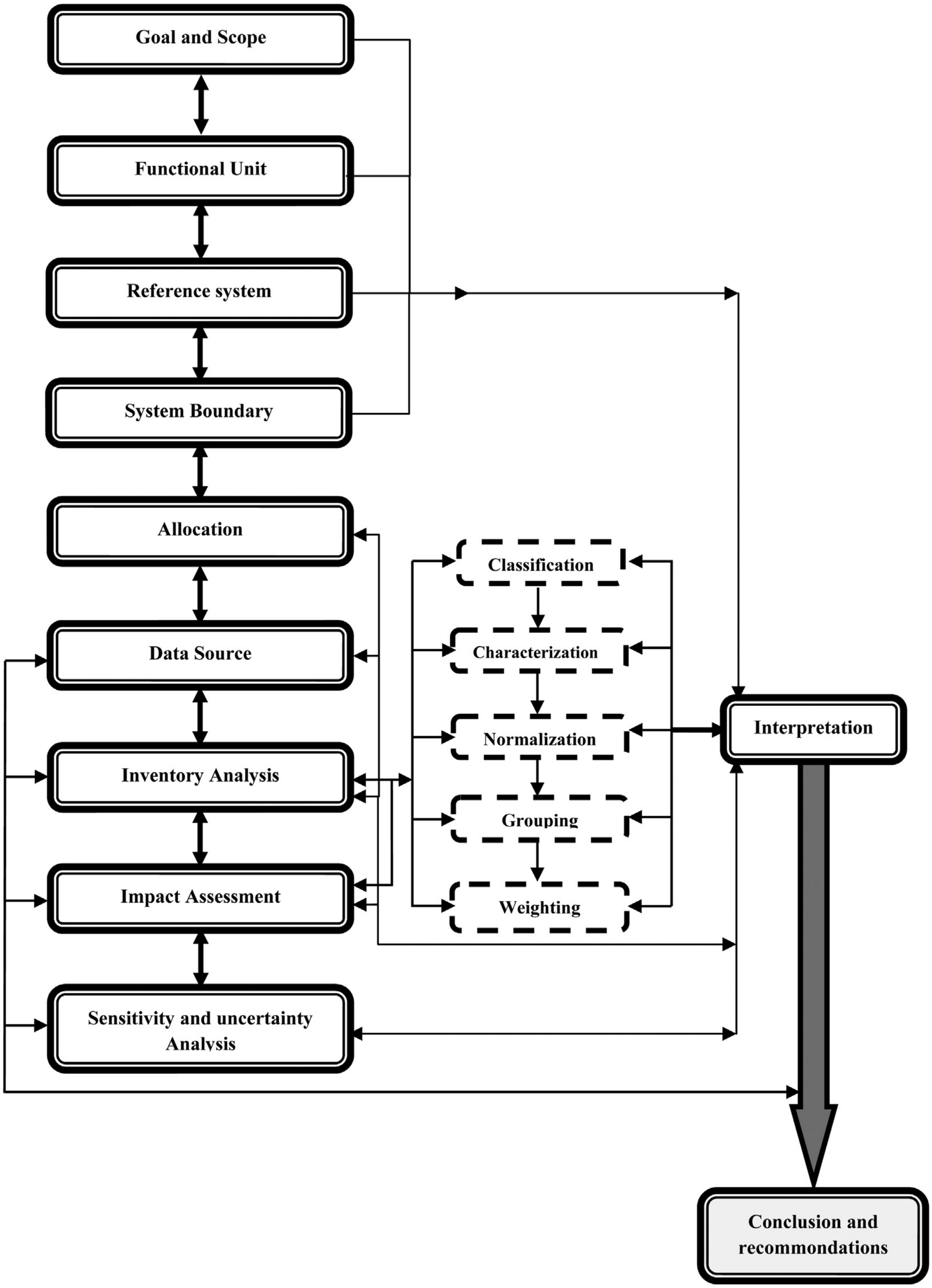

Fig. 1. Various phases of Life Cycle Assessment (Adapted from Rathore et al., 2013).

ozone and respiratory inorganic (Nguyen et al., 2013; Kimming et al., 2011).

The above LCA discussions suggest that, residue bioenergy have certain environmental superiorities over conventional fuels, if utilized in a sustainable way. However, since the same biomass feedstock can be used through multiple energy conversion routes (heat, electricity, bioethanol), therefore it is important to identify the most beneficial route of conversion. In this regard, Cherubini et al. (2009) reported that (i) production of heat and electricity from biomass has higher GHGs emissions reduction and energy saving benefits than the production of biofuel, (ii) waste/residue biomass shows best environmental performance, since they avoid both the impacts of energy crop production and the emissions from waste management. For enhanced GHGs emissions reduction, Muench (2015) recommended deployment of (i) non-dedicated ligno-cellulosic biomass with thermo-chemical conversion, (ii) dedicated ligno-cellulosic biomass with thermo-chemical conversion and (iii) dedicated ligno-cellulosic biomass with direct combustion. Use of biomass waste/residue has also been suggested as a better emission reduction option than replacing existing

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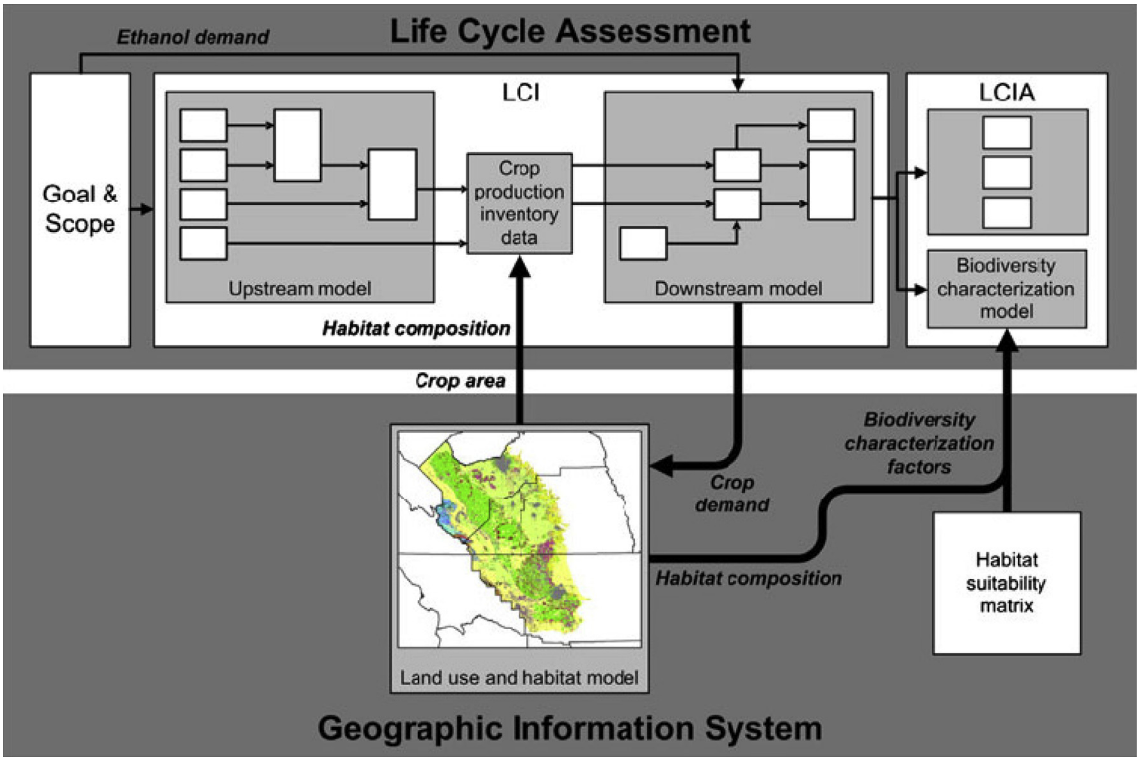

Fig. 2. A procedure to integrate GIS into LCA for the assessment of environmental implications of biofuel production (Geyer et al., 2010). The interface between GIS and LCA are indicated by bold arrows. Here, GIS provides land use land cover and biodiversity habitat data to the LCA framework to identify the bioenergy impact on biodiversity elements.

croplands or clearing new lands for energy crop plantation (Fargione et al., 2008; Searchinger et al., 2008; Ho et al., 2014).

5. Uncertainties in bioenergy LCA

As discussed in the previous section, though the environmental benefits of bioenergy over fossil energy has been realized through LCA studies, however, there are some uncertainties related to LCA applicability (Hellweg and Canals, 2014). The variations may be due to the differences in the type and management of raw materials, conversion technologies, end use technologies and the choice of LCA methodologies (consequential/attributional/hybrid LCA) (Cherubini et al., 2009; Muench, 2015; Muench and Guenther, 2013). Lack of general consensus regarding the definition of the system boundary, fossil reference system, optimal functional unit, ideal allocation of environmental impact between products and co-products, modelling carbon cycle of biomass (biogenic/non-biogenic carbon flow) also lead to variations (Muench and Guenther, 2013; Choudhary et al., 2014). In addition, the collection of actual data for LCA study is a challenging task, as these datasets may vary temporally and spatially (Singh et al., 2013). Allocation is a very sensitive issue in LCA which affects the results significantly. The inappropriate allocations could lead to incorrect LCA results. Allocation is a procedure of appropriately allocating the environmental burdens of a multi-functional process among its functions or products (Reap et al., 2008). Allocation step is one of the determining steps that tell how much of the environmental burden caused by a multi-functional process should be apportioned to each product or function (Singh and Olsen, 2012). Plevin et al. (2014) cautioned that LCA results should refrain from using unsupported claims, such as "*using product X results in a Y% reduction in GHG emission compared to product Z*" because such claims are valid only in rare cases.

The limitations of LCA must be taken into account while conducting bioenergy LCA. Hellweg and Canals (2014) suggested that it is a duty of the LCA practitioners to explain to the decision makers that LCA is not always a tool to provide a single answer, but it gives a comprehensive understanding of a problem and its possible solutions. Muench (2015) recommended numbers of ways to increase the reliability of LCA results which includes: (i) LCA can be further improved by accounting for heterogeneity among biomass systems, (ii) the strong influence of small differences in biomass systems must be considered while interpreting the LCA results, (iii) transferability of LCA results between similar systems must always be investigated, (iv) adopting assumptions from other systems should be avoided since it may lead to errors, (v) analysis of GHGs emissions mitigation potential is only a first step in assessing the sustainability of biomass derived electricity and hence future LCA research should include additional environmental, economic and social impact categories. Further, it should also be noted that since a real life situation is modelled in LCA, so, there is a possibility of distortion of the reality in the model outcome (Goedkoop et al., 2013). Hence, developing LCA model with prior knowledge of the system under investigation and careful selection of the system parameters is important to minimize bias between reality and model output and gain a true picture of the environmental benefits of bioenergy.

6. Spatial LCA in bioenergy and environmental planning

Due to the distributed nature of biomass resources, environmental impacts of bioenergy may have spatial consequences too, especially with regards to land use and biodiversity. Excluding the impact on biodiversity in LCA studies can significantly limit the applicability of LCA findings (Geyer et al., 2010; Baan et al., 2013). In many bioenergy LCA studies, average country level values are taken as input data. However, parameters such as grain productivity, residue to grain production ratio, surplus residue availability, competing uses of residue may vary from region to region. Thus, considering country level average data for local or regional representation may lead to erroneous result. This is particularly true for large scale biomass power plants, where feedstocks are collected from large geographical areas. Traditional LCAs are unable to recognize the spatial dimension of environmental impacts of bioenergy but it can be addressed if the LCA is conducted on a GIS platform (Geyer et al., 2010). Use of Information Technology supported LCA enables to analyze and visualize material flows, processes or products and the calculation of eco-balances on spatial scale (Dresen and Jandewerth, 2012). Applying spatio-temporal models can improve the spatial and temporal depths of LCA analysis (Arodudu et al., 2017). Regionalized LCA using spatial platform increases the accuracy of assessment by accounting site-specific production conditions along with differences in transport and the sensitivity of ecosystems (Hellweg and Canals, 2014). However, limited literature is available on spatial LCA. Therefore, the following discussion is not limited to residue bioenergy but various forms of bioenergy are also covered.

Land use impact on biodiversity is difficult to predict because of the spatial heterogeneity of biodiversity and unavailability of precise impact assessment tool (Geyer et al., 2010). The integrated use of GIS and LCA (spatial LCA) could give important insight into how land use change could impact biodiversity. Geyer et al. (2010) presented a *proof-of-concept* (Fig. 2) by integrating GIS and LCA together for impact assessment of ethanol production on land use and biodiversity in California. The study found that GIS based inventory modelling of land use allows important refinement in LCA and using GIS, land use can be modelled as a geospatial and nonlinear function of output. Humpenoder et al. (2013) combined GIS based LandSHIFT model with LCA to investigate the land use impact on the carbon balance of biofuel in the European Union (EU). The results indicate that land use change has a major impact on the GHGs emissions performance of biofuel. In a different study, Geyer et al. (2013) presented a spatial LCA approach of sun-to-wheels energy conversion pathways in the US considering land use impacts, life cycle GHGs emissions and fossil fuel demand for five different sun-to-wheels conversion pathways. Azapagic et al. (2013) developed a decision support system called PUrE which integrates several environmental assessment tools in one platform for sustainability assessment of human activities on the urban environment. The sub-components of the tool includes GIS, LCA, substance flow analysis (SFA), air dispersion modelling (ADM), health impact assessment (HIA) and multi-criteria decision analysis (MCDA). Gasol et al. (2011) conducted a spatial LCA study to investigate decentralized bioenergy potential based on *Brassica* spp. and *Populus* spp. The GIS is used to estimate bioenergy production while the LCA is applied to estimate potential CO_2 emission reduction from bioenergy power plants. Mutel et al. (2012) proposed a GIS combined LCA method for regionalized LCA on spatial platform using Brightway software which directly includes GIS capabilities in the LCA calculation. Dresen and Jandewerth (2012) combined geoinformatics with LCA to conduct spatial analysis of biogas production in Germany. Under the HEDGE-BIOMASS project, Ferrarini et al. (2014) proposed a combination of GIS, LCA and SWAT model to investigate landscape level bioenergy production in order to identify how and where bioenergy can be produced sustainably and how to optimize the trade-off between delivery of multiple ecological services and farmers benefit within limited land resources. Integration of GIS into LCA for impact assessment of algal biofuel production from wastewater has also been recently reported by Roostaei and Zhang (2016).

7. Conclusions

The role of GIS, LCA and spatial LCA in agro-residue bioenergy planning is discussed in this paper. GIS is important for distributed resource assessment while LCA is used to evaluate environmental consequences of bioenergy generation. Residue bioenergy provides distinct environmental benefits over conventional energy systems. For assessment of certain spatial environmental impacts of bioenergy, the use of spatial LCA is necessary, however, there are some uncertainties in LCA methodologies that can limit its applicability in sound decision making. It is recommended that every bioenergy project should include Life Cycle Assessment (LCA) as a fundamental project development component.

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