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Development of tortuosity factor for assessment of lignocellulosic biomass delivery cost to a biorefinery

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HIGHLIGHTS

- A framework is developed for estimation of tortuosity factor for biomass transport.
- GIS is used to calculate the tortuosity factor for western Canada.
- Tortuosity factor for the Province of Alberta in Canada is in the range of 1–3.16.
- This methodology helps in accurate assessment of biomass delivery cost.

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ABSTRACT

The tortuosity factor of road infrastructure is an important parameter for assessing and designing biofuel facilities. This study focuses on the assessment of tortuosity factor considering real road network and dispersedly lignocellulosic biomass resources. A methodology is developed and applied under this study to estimate the tortuosity factor (τ) using GIS software. It is shown that τ varies considerably with plant capacity and in different plant locations. The estimated values of τ in the case study (Alberta) are in the range of 1–3.16 and average values are 2–8% larger than the theoretical value (1.27). The unit cost of transportation is more sensitive to tortuosity factor at larger plant capacities. This methodology can be applied for other jurisdictions to assess the accurate lignocellulosic biomass delivery cost using the actual road network.

1. Introduction

Lignocellulosic biomass from field or forest can be used for production of fuels and chemicals in a biorefinery. Design and management of logistics system for lignocellulosic biomass supply is a critical factor for development of a biorefinery. The supply and logistics system is dependent on type of biomass feedstock and geography of a region in which biorefinery is located. These systems for biomass help in determining the delivery cost of biomass to a biorefinery. There has been a significant amount of research attention on assessment of biomass delivery cost to a biomass-based facility. For example, Allen et al. [1] developed biomass (forest fuel, short rotation copprice, straw, miscanthus) supply chain model including delivery cost of supply of biomass fuels to biomass power stations in UK. Angus-hankin et al. [2] determined biomass delivery cost from forest to the utilization facility emphasizing on improvement of biomass carrying efficiency of truck by incorporating pre-treatment such as making chips, pellets, and bundle. The receiving, handling, storing and processing of woody biomass feedstocks especially forest residue, industrial mill residue, urban residue and their costs for direct combustion, gasification and also small module biopower system in USA were assessed by Badger [3]. Hess et al. [4] reported optimal feedstock flow system from production site to biorefinery in USA and determined feedstock (wheat and barley straw) assembly cost including harvest, collection, transport and storage along with conversion cost. The delivery cost associated with long distance bioenergy transport system in different forms such as log, pellet and liquid fuel for biopower and methanol production in Latin-America and European setting were discussed in Surr [5]. The biomass delivery cost is a major part of biofuel production cost; lignocellulosic biomass delivery cost constitutes 35–50% of total cost of production [6–9]. The high component of biomass delivery cost is a key contributor to total cost of production of fuels and chemicals in a biorefinery. Making these biorefineries competitive with the fossil fuel based facilities is a challenge and there is a critical need to reduce the delivered cost of lignocellulosic biomass.

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Transportation cost of lignocellulosic biomass is one of the main components of the biomass delivery cost. It depends on the geographical distribution of biomass sources, the location of the biomass utilization plants, the transport infrastructure configuration which vary from location to location, the mode of transport and characteristics and forms of biomass [7]. Consequently, the design and development of a sustainable biofuel industry requires proper consideration of transportation cost. For a particular region, biomass resource characteristics and road network infrastructure play a significant role when determining the lignocellulosic biomass delivery cost. Application of spatial information technologies such as remote sensing and geographic information system (GIS) in addressing this issue appear to be an appropriate methodology. In the past, GIS has been used for addressing biomass availability and identifying location of the facilities in different studies. Noon and Daly [10] developed a GIS-based decision support system in estimating biomass resource potential and cost of supplying biomass to coal-fired power plant. Another study developed GIS supported methodology in order to assess the technical and economic potential of biomass extraction for energy production [11]. The use of GIS for estimating biomass supplies and modeling system for evaluating the cost of delivered energy crop feedstocks [12]. GIS has been used in another study by Haddad and Anderson [13] to identify potential location in Midwestern region for collection and storage of cornstover for use as a feedstock. Noon et al. [14] also used GIS based application methodology for the identification of promising location for switchgrass to ethanol conversion facility. Panichelli and Gnansounou [15] study presents a GIS-based decision support system for selecting least cost bioenergy location when there are variability in the farmgate price of biomass and more than one facility has to be placed in the region.

During planning and designing stage of a biomass-based facility, generally, the complexity of real road network is critical and is represented by a tortuosity factor [16]. Ranta [17] determined biomass potential and designed supply chain logistics based on regional characteristic of resources and road infrastructure. Tortuosity factor is defined as the ratio of actual travel distance via the roads to the shortest straight line distance (or the line of sight distance). This factor is applied to approximate the transporting distance via the road network between the biomass collection points and the plant where biomass is used. This is an important parameter in accurately determining the transportation cost to any biomass-based plant. If other factors remain the same, lignocellulosic biomass facility should be built in the area where tortuosity factor of transportation network is lowest to get minimum delivered cost of lignocellulosic biomass. The equation of determining total transportation cost ($/tonne) in generic approach can be depicted as

$$TC = a + b\mathcal{T}X \tag{1}$$

where TC = transportation cost of biomass ($/tonne); a = fixed cost parameter ($/tonne); b = variable cost parameter ($/tonne-km); X = roundtrip distance (km); and $\mathcal{T}$ = Tortuosity factor. The fixed component of the cost (a) of truck transportation is the cost of loading and unloading cost ($ tonne^{-1}). The variable component of the cost of truck transportation (b) includes cost of wages for the driver, fuel, and maintenance ($ $\text{tonne}^{-1}\,\text{km}^{-1}$). These variable costs are proportional to the distance travelled and changes with transportation distance. The typical loading and unloading cost for truck transportation in North America is $5.45 green tonne^{-1} [18]. The variable transportation cost of truck is $0.22 green $\text{tonne}^{-1}\,\text{km}^{-1}$ [19].

Earlier different studied has estimated transportation cost of different types of biomasses using generic approach. In most of the cases biomass collection is considered circular [20,21] and other cases collection area is considered rectangular [22]. In the generic approach, a techno-economic model is developed with some assumptions. In most of the studies, a circular biomass procurement area was taken to estimate the transportation cost of biomass to the plant and the distribution is biomass is considered uniform within the circular area. The average transportation distance from the centre of the circular area to the point of collection is considered 2/3r, where r is the radius of circular area. However, this road distance may not be a straight line in real case from the collection point to the plant. Generally, a factor is used to consider the waviness of real configuration of the road. This factor is generally called tortuosity factor. Different studies show whose value varies between 1 and 3. But none of the studies shows the any rational for considering that value or systematic procedure of its determining. Most of the studies adapted and used this value from earlier studies.

Different studies have shown the importance of the infrastructure in which lignocellulosic biomass supply system operates [23,24]. Earlier studies have mentioned the significance of tortuosity factor and road properties for determining lignocellulosic biomass transport and delivery cost [24–27]. Leboreiro and Hilaly [28] compared different transportation schemes for transporting biomass from farm to processing facility by applying winding factor. Ravula [29] determined tortuosity factors of road networks by using geographic information system (GIS) and by splitting the entire region into concentric circles. Similar method was used by Mukunda et al. [30] for lignocellulosic biomass availability assessment. Different values of the tortuosity factor were used in earlier studies which vary from 1 to 3 for cost estimation or determination of plant capacity. For example, Wright and Brown [31] used a tortuosity factor of 1.5 for estimation of delivery cost for corn stover; Sarkar and Kumar [32] and Sultana et al. [33] used a tortuosity factor of 1.27 for estimation of delivery cost for woody biomass and straw; Leduc et al. [25] used a tortuosity factor of 1.4 for estimation of delivery cost for woody biomass; Perlack and Turhollow [34] and Zhang et al. [35] used a tortuosity factor of 1.30 for estimation of delivery cost for corn stover. However, the systematic procedure of estimating tortuosity is unavailable.

Although tortuosity factor is one of the important parameters for biofuel facility development, there is hardly any research reporting systematic assessment of tortuosity factor for a particular region. In most of the studies, the rationale for assessment of assumed values of tortuosity factor is generally not based on scientific rigor. Most of the previous studies have assumed a single value of the tortuosity factor for the whole region. Generally, tortuosity factor will vary depending on the road infrastructure, lignocellulosic biomass sources and biomass-based plant locations. One of the critical aspects related to the tortuosity factor is that it is dependent on the plant capacity. As the size of the plant based on biomass increases, the area required to supply the biomass is more and hence the transportation distances increases. This impact on the tortuosity factor has not been addressed in the literature earlier. This study aimed to develop a framework to estimate tortuosity considering disperse distribution of biomass and real road infrastructure.

The objectives of this research include:

- Development of a framework to assess the tortuosity factors for a particular region.
- Use this framework to develop tortuosity factors based on data comprising of dispersed lignocellulosic biomass distribution and real road network which links with the capacity of plants using GIS.
- Demonstrate the methodology through a case study for development of tortuosity factors for the Province of Alberta in Canada which has large availability of lignocellulosic biomass.