

The biofuel potential of municipal solid waste

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Abstract

The world in the 21st century is facing a dual crisis of increasing waste and global climate change. Substituting fossil fuels with waste biomass-derived cellulosic ethanol is a promising strategy to simultaneously meet part of our energy needs, mitigate greenhouse gas (GHG) emissions, and manage municipal solid waste (MSW). However, the global potential of MSW as an energy source is as yet unquantified. Here, we report increasing trends of MSW generation, and waste biomass-derived cellulosic ethanol potentials in relation to socio-economic development across 173 countries, and show that globally, up to 82.9 billion litres of waste paper-derived cellulosic ethanol can be produced worldwide, replacing 5.36% of gasoline consumption, with accompanying GHG emissions savings of between 29.2% and 86.1%.

Keywords: biofuels, cellulosic ethanol, municipal solid waste, waste paper

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Introduction

In recent years, the energy and climate crises have come to the forefront of public awareness. In 2007 the Intergovernmental Panel on Climate Change (2007) reported 'unequivocal' evidence of warming of the climate system, and that much of this is 'very likely' owed to anthropogenic greenhouse gas (GHG) emissions. Despite political and scientific advances in environmentally friendly policies and technologies, there still remains much work to be done to make our lifestyles more sustainable and ecologically sensitive. First-generation biofuels – those derived from food crops such as corn ethanol and soy biodiesel – are known to involve multiple environmental and social trade-offs such as net positive GHG emissions from land use change, and threats to global food security, among others (Fargione *et al.*, 2008). Second- or third-generation biofuels, such as those derived from waste biomass, are widely recognized to be the way forward in biofuels research (Scharlemann & Laurance, 2008), and promise real emissions savings over fossil fuel use (Ragauskas *et al.*, 2006).

Coincidentally, as urban populations increase worldwide, the management of municipal solid waste (MSW) is rapidly becoming challenging, because the common approach of landfilling or incinerating our waste often results in adverse environmental impacts (Lou & Nair,

2009). In this paper, we seek to quantify the global potential of MSW as an energy source by modelling the relationships between socio-economic development and (i) MSW generation, in the form of waste biomass-derived cellulosic ethanol potentials, and (ii) gasoline consumption. We then use these models to estimate the fossil fuel replacement and GHG savings potentials of waste biomass-derived cellulosic ethanol for 173 countries.

Materials and methods

Waste biomass-to-cellulosic ethanol conversion efficiencies

Our estimates of waste biomass-to-cellulosic ethanol conversion efficiencies were derived from three recent studies. The lowest estimate was based on Mtui & Nakamura (2005), who studied bench-scale conversion of lignocellulosic MSW to ethanol. Their results for ethanol production obtained using feedstock that was 93% lignocellulosic and contained mainly paper waste were 150 g kg⁻¹ waste. Champagne (2007) estimated that 300 L of cellulosic ethanol can be produced from each megagram of dry crop residue biomass. Assuming that waste paper and cardboard are similar to crop residues in chemical composition, and contain up to 50% water by weight, we derived a waste paper-to-cellulosic ethanol conversion efficiency of 236.7 g kg⁻¹. Lynd *et al.* (1991) estimated that 0.33 kg of cellulosic ethanol can be produced from each kilogram of dry

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wood feedstock. Assuming that wood waste contains an average moisture content of 30% (w/w), we estimated that approximately 0.23 kg of ethanol can be produced from each kilogram of wet wood waste, and derived a conversion efficiency of 236.7 g kg⁻¹.

GHG savings potential

In this analysis, GHG emissions data were obtained from the Global Emissions Model for Integrated Systems (GEMIS, 2009) as well as L-B-Systemtechnik (2002), and used to generate a range of potential GHG emissions reductions per unit energy in CO₂ equivalents (CO₂Eq) MJ⁻¹ of embodied energy. In this analysis, we assumed firstly that the system boundaries for waste-to-biofuels begin with waste entering the refinery. Prior life cycle impacts of the waste material are ignored, except for the initial carbon fixation by photosynthesis. Similarly, the exit boundary was defined as the point at which the fuel leaves the refinery. For fossil fuels, the system boundary extends from the point of extraction (e.g. of crude oil) to the point of collection just before distribution. The emissions values were thus comparable because they both take into account all the processing required between raw material and finished product. This analysis also discounted all GHG emissions associated with the actual burning of the fuels, because we assumed that all fossil fuels and biofuels, regardless of source, originate from plant matter containing an equivalent amount of fixed carbon. Such studies typically account for the waste management of ethanol conversion co-products but do not claim carbon credits for these materials (Kalogo *et al.*, 2007). There was some disparity between the emissions estimates from different studies (Kalogo *et al.*, 2007; Chester & Martin, 2009; Shi *et al.*, 2009), owing to varying assumptions on energy sources and process details. Therefore, we present our results in terms of a possible range of percentage GHG reduction per unit fossil fuel energy replaced. These estimates, however, were for the processing of cellulosic ethanol from waste straw, since data for other specific forms of waste plant biomass (e.g. paper or cardboard) were not available.

Modelling of waste generation and gasoline consumption

We gathered data on waste paper and cardboard generation from multiple sources (Table S1). We focused on waste paper generation because it was the municipal cellulosic waste stream with the most complete data. Even so, data on waste paper and cardboard generation were only available for 71 countries. Therefore, we fitted a simple linear regression model to the available data on waste paper and cardboard generation and a measure of

socio-economic development – the Human Development Index (HDI) – and used this model to estimate waste paper generation for 173 countries (Table S1). Waste paper and cardboard generation is likely to be influenced by multiple socio-economic factors within each country. HDI is a composite index developed by the United Nations Development Programme to comprehensively describe human development (<http://hdr.undp.org/en/>) – comprising proxies for health care and living conditions (Life expectancy), education (Adult literacy) and disposable income (Gross Domestic Product per capita). Therefore, we chose HDI as the socio-economic variable upon which to model both waste generation and gasoline consumption.

Next, we fitted a linear regression model to the available data on gasoline consumption and HDI ($n = 129$), and used this model to estimate gasoline consumption for the 173 countries considered in this study. Gasoline consumption data were obtained from the Earthtrends database of World Resources Institute (2009). In our analysis, we assumed that each unit of cellulosic ethanol has the energy content equivalent to 0.61 units of gasoline.

Results

Our model of waste paper and cardboard generation and the HDI explained 57.3% of the variation. This model suggests that the amount of waste paper generated per capita and per annum by a country increases exponentially with its HDI, and ranges from 1.2 kg capita⁻¹ in Sierra Leone to 162.2 kg capita⁻¹ in Norway (Fig. 1).

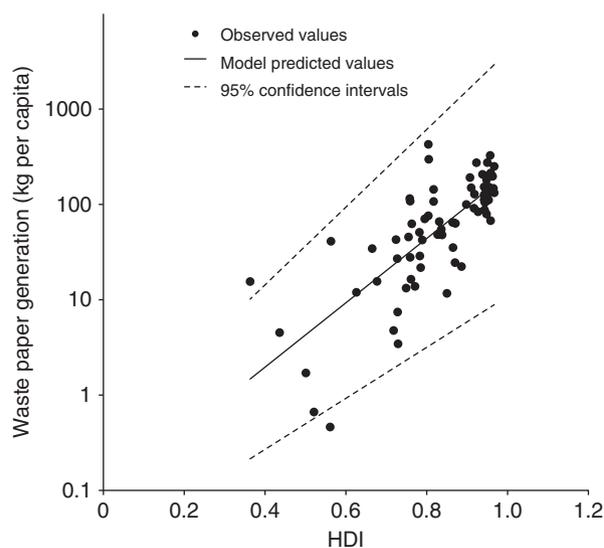


Fig. 1 Linear regression model fitted to available data on waste paper generation and HDI ($n = 71$). The resultant model is described by the equation: waste generation (in kg capita⁻¹) = $10^{(3.375 \cdot \text{HDI} - 4.057)}$; $r^2 = 0.573$; $P < 0.001$.

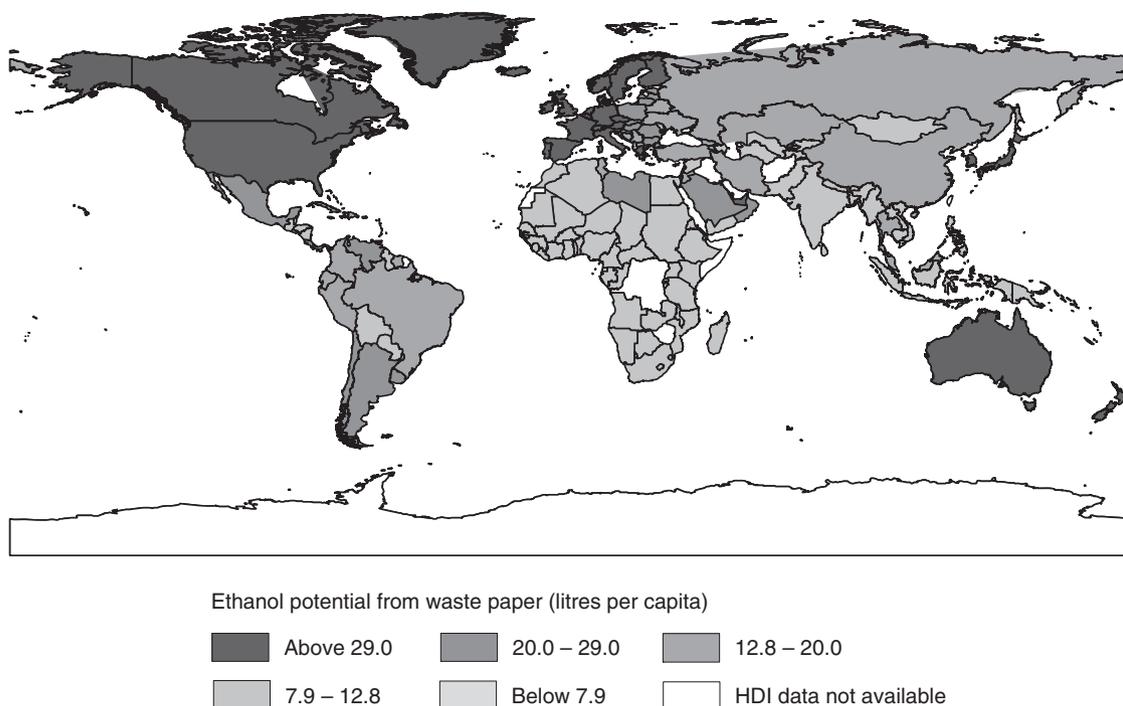


Fig. 2 Estimated maximum cellulosic ethanol potential (litres per capita) from waste paper for 173 countries plotted onto World map.

Based on our assumption of waste biomass-to-cellulosic ethanol conversion efficiencies of between 15% (w/w) and 23.67% (w/w), our analysis shows that cellulosic ethanol production from waste paper could potentially amount to 82.93 billion litres globally, and ranges from 0.226–0.356 L capita⁻¹ in Sierra Leone to 30.7–48.4 L capita⁻¹ in Norway (Fig. 2).

Our second model using the HDI accounted for 74% of the variation in country-level gasoline consumption, and predicted a global gasoline demand ranging from 4.3 L capita⁻¹ in Sierra Leone to 547.7 L capita⁻¹ in Norway. By comparing the model for waste generation with that of gasoline consumption, we found that globally, cellulosic ethanol from waste paper could potentially meet 5.36% of transport gasoline demand (Table S1).

The estimated GHG emissions associated with 1 MJ of fossil fuel gasoline range from 2.419–12 g CO₂ equivalents; whereas for cellulosic ethanol, the estimated emissions range from 0.336–8.5 g CO₂ Eq MJ⁻¹ of energy. Examining the percentage GHG savings described by the data sources, we estimated that the substitution of gasoline use with waste paper-derived cellulosic ethanol could offer GHG savings of between 29.2% and 86.1%, which is consistent with estimates from Kalogo *et al.* (2007).

Discussion

The estimates reveal that, globally, the production of cellulosic ethanol from waste paper and cardboard

could potentially amount to 82.9 billion litres. If cellulosic ethanol technology continues to improve and mature, these numbers are certain to increase, in which case cellulosic ethanol may be an important component of our renewable energy future. Several lines of research in cellulosic ethanol are also expected to improve yields and promise even greater reductions in GHG emissions (Stephanopoulos, 2007; Sánchez & Cardona, 2008). The potential for waste derived cellulosic ethanol as a fuel source is therefore promising.

Our HDI-based model explains 57.3% of the variation in waste generation between countries. Undoubtedly, there are other factors that influence waste generation, including cultural differences and patterns of consumption, which are more complex to quantify. There is also a need for future models to take into account other forms of waste cellulosic biomass including vegetable waste and discarded wood, which comprise a significant portion of the MSW stream. Furthermore, demands for these waste materials from the recycling industry need to be assessed as potential competing uses for biomass feedstocks, and which might therefore influence their availability and costs. Recent research, furthermore, has demonstrated that, owing to the relatively low efficiency of the internal combustion motor, converting a given amount of biomass to bioelectricity rather than cellulosic ethanol may yield a higher net transportation output (Campbell *et al.*, 2009). However, the authors do admit that there are other criteria in

evaluating a fuel pathway and refrain from recommending bioelectricity over cellulosic ethanol.

While the potential contribution of other biomass sources, such as agricultural residues and biomass plantations, have been increasingly studied (Berndes *et al.*, 2003), the biomass potential of MSW has received relatively little attention. Our results suggest that cellulosic ethanol from waste biomass is a promising clean energy solution that could simultaneously meet part of our energy needs, mitigate GHG emissions, and mitigate the impact of increasing material consumption. Waste biomass-derived cellulosic ethanol should therefore be part of a diverse portfolio of renewable energy sources for a sustainable future.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Country-level data for Human Development Index (HDI) in 2006, per capita waste paper and cardboard generation in kilograms (WASTE), per capita gasoline consumption in liters (GASOLINE), per capita waste paper-derived cellulosic ethanol potential in liters (BIOFUEL), gasoline-with-cellulosic ethanol replacement potential (REPLACE), and the resultant greenhouse gas emissions savings from gasoline use (GHG).

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