BIOMASS AND BIOENERGY 63 (2014) 210–217

Available online at www.sciencedirect.com

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Compositional analysis and projected biofuel potentials from common West African agricultural residues

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ARTICLE INFO

Article history:
Received 10 January 2013
Received in revised form
11 October 2013
Accepted 31 January 2014
Available online 28 February 2014

Keywords:
West Africa
Biomass
Residue
Composition
Bioethanol
Biogas

ABSTRACT

In recent years the focus on sustainable biofuel production from agricultural residues has increased considerably. However, the scientific work within this field has predominantly been concentrated upon bioresources from industrialised and newly industrialised countries, while analyses of the residues from most developing countries remain sparse. In this study the theoretical bioenergy potentials (bioethanol and biogas) of a spectrum of West African agricultural residues were estimated based on their compositions. We analysed 13 of the most common residues: yam peelings, cassava peelings, cassava stalks, plantain peelings, plantain trunks, plantain leaves, cocoa husks, cocoa pods, maize cobs, maize stalks, rice straw, groundnut straw and oil palm empty fruit bunches. The yam peelings showed the highest methane and bioethanol potentials, with 439 L methane (kg Total Solids)$^{-1}$ and 0.61 L bioethanol (kg TS)$^{-1}$ based on starch and cellulose alone due to their high starch content and low content of un-biodegradable lignin and ash. A complete biomass balance was done for each of the 13 residues, providing a basis for further research into the production of biofuels or biorefining from West African agricultural residues.

1. Introduction

Following the 2007 report from the Intergovernmental Panel on Climate Change (IPCC) [1], the role of the greenhouse gas (GHG) effect on the climate has been widely accepted in the scientific community [2,3]. At the same time, increasing fuel prices have massively increased the focus on energy security and energy independence globally, regionally, and locally [4–6]. One of the responses to the above-mentioned issues is increased focus on sustainable biofuels, since biofuel production can potentially reduce GHG emissions and yield energy.

The biofuels policies of many countries, currently fail to satisfy ethical principles of, e.g. environmental sustainability and equitable distribution of costs and benefits among stakeholders [7]. In that sense, these policies are still counterconstructive in terms of the most obvious environmental goals. However, there are other incentives for encouraging biofuels production besides its potential as a source of GHG

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http://dx.doi.org/10.1016/j.biombioe.2014.01.045

neutral energy. Ejigu (2008) [8] found that in an African context modern bioenergy offers tremendous opportunities to meet growing household energy demands, increase income, reduce poverty, and mitigate environmental degradation. Mangoyana (2009) [9] also argued that in an African setting biomass energy production could be an effective way of achieving sustainable development that is less land intensive, has positive net energy gains and environmental benefits, and provides local socio-economic benefits. However, despite the wide interest in biomass for energy production, scaling up experimental projects to commercial operations is far from easy, to a certain extent due to lack of investment capital but also due to lack of interdisciplinary approaches that account for the specific dynamics and interrelationships between environmental and socio-economic systems of the West African context [10]. A thorough knowledge of agricultural residues that can be used for biofuel estimations is a necessary starting point, in order to reveal such dynamics and interrelationships.

1.1. *Residues from West Africa*

Dealing with bioenergy from a scientific approach, the main focus has until now been on residues from industrialised countries or from newly developed countries e.g. China [11–13]. Such well-investigated residues include: maize stalks [14], wheat straw [15], rye straw [16], grasses [17,18], legumes [19,20], sugar cane bagasse [21], and rice straw [22]. On the other hand, the agricultural residues most common to developing countries of West Africa have not yet been prioritised.

According to the Food and Agriculture Organisation of the United Nations [23] residues from archetypical West African crop include yam peelings, cassava peelings, cassava stalks, plantain peelings, plantain trunks, plantain leaves, cocoa husks, cocoa pods, maize cobs, maize stalks, rice straw, groundnut straw and oil palm empty fruit bunches (EFB). Of those 13 West African residues, the peelings from yam and cassava are partly used for animal feed, but only the cassava stalks have previously been evaluated for their composition by Martin et al. (2006) [24]. Plantain residues have not yet been assessed. A few studies have addressed a closely related banana residue, but they did not compare it with other residues [25]. Cocoa residues, as well as groundnut straw, have mainly been considered for animal feed and therefore some information required for bioenergy evaluations is missing [26–28]. Oil palm EFB has been studied by several authors, but with large deviations in the published results which justifies improved investigation [29,30]. Internationally common residues such as maize cobs, maize straw and rice straw have been thoroughly investigated [31,32], but not on residues originating from West Africa.

1.2. *Biomass characterisation and bioenergy potentials*

Since the beginning of the last century, great effort has been invested in investigating the composition of residues [33,34]. However, within optimal utilisation of the residues for bioenergy purposes, some features have not yet been scientifically addressed.

Ethanol fermentation is facilitated by pure cultures of microorganisms which metabolises only sugars, and calculating a theoretical bioethanol potential from the composition of the materials depends both on the biomass constituents and on the kind of fermenting microorganism applied. The traditional substrate for ethanol fermentation is free C6 sugars often originating from hydrolysed starch. Since some waste residues are containing free sugars and/or starch this traditional and simple way is investigated. However, present day's bioethanol can be produced as a sustainable fuel based on complex lignocellulosic residues with a wide range of different sugar monomers. Wild-type *Saccharomyces cerevisiae* strains readily ferment glucose, mannose and fructose, galactose as well as the disaccharides sucrose and maltose (C6 sugars), and therefore this has been the organism of choice for centuries [35,36]. On the other hand, other of the most abundant sugar monomers from biomass D-xylose, L-arabinose, galacturonic acid and L-rhamnose (C5 sugars) requires either extensive metabolic engineering of *S. cerevisiae* [35] or other fermentative organisms such as *Kluyveromyces marxianus* [37], *Zymomonas mobilis* [38], *Pichia stipitis* [37], or the thermophilic anaerobic bacterium *Thermoanaerobacter* [39]. However, the challenge in C5 sugar fermentation is now to successfully transfer strains and concepts from the laboratory to industrial conditions, which opposes multiple challenges [35].

Whereas ethanol fermentation is facilitated by pure cultures of microorganisms, biogas is produced by a mixed natural consortium of microorganisms. Therefore, the anaerobic biological degradation of organic matter to produce biogas is a process found in many anaerobic habitats such as sediments, rice paddies, open manure silos, landfills, waterlogged soils, and in the mammalian gut [40,41]. The same processes that take place in these habitats can be controlled and utilised to convert various biomass constituent, such as carbohydrates, proteins, lipids, sugar alcohols, fatty acids and more, into methane-rich biogas as a very resource efficient and environmentally friendly way of producing energy [42]. The theoretical biogas yield can be estimated from the biomass constituents of a residue with Buswell's formula [43,44], or it can be computed from the chemical oxygen demand (COD) of the residues [44].

In this study, we thoroughly analysed 13 archetypical West African agricultural residues and we are presenting complete chemical composition of these residues. In addition, we estimate three different ethanol potentials: (1) based on starch and free sugars, (2) based on all C6 sugars fermentable by *S. cerevisiae*, and (3) a potential if all available sugars are utilised. Furthermore, we estimate theoretical maximum biogas potentials both based on compositional data calculated with Buswell's formula, and based on COD content.

2. Materials and methods

2.1. *Raw materials*

The agricultural residues were obtained from the test facilities of the Ghana Crops Research Institute of the Council for