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Mapping the Conversion Potential of Agricultural Residue Cellulose into Bioethanol Using National Crop Production Data: A Theoretical Mass Balance Approach

Kinia Mitasari [1] *

[1] Universitas Pendidikan Indonesia

* Correspondence: mitasarikinia@gmail.com

ABSTRACT

Global dependence on fossil fuels drives urgent energy and environmental crises, necessitating sustainable alternatives like second-generation bioethanol from lignocellulosic agricultural residues, which avoids food crop competition. This study maps Indonesia's theoretical maximum bioethanol potential from rice straw, corn residue, and sugarcane bagasse cellulose using 2023 national crop production data from BPS integrated with stoichiometric mass balance calculations assuming 100% hydrolysis (1.11 factor) and fermentation (0.511 factor) efficiency. Results show 86.78 million dry tons of total residue yielding 37.24 million tons theoretical glucose and 19.03 million tons bioethanol, equivalent to 24.12 billion liters annually, with rice straw contributing over 70%; at 50% realistic efficiency, potential reaches 12.06 billion liters. These findings establish a data-driven benchmark for policymakers, highlighting abundant untapped biomass for energy diversification while noting limitations like process inefficiencies and residue sustainability needs.

Keywords: bioethanol; agricultural residue; lignocellulose; mass balance; Indonesia; rice straw

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1. Introduction

Global reliance on fossil fuels has initiated a pressing environmental and energy crisis, necessitating a swift transition towards more sustainable and renewable energy sources [1]. Second-generation bioethanol, derived specifically from lignocellulosic biomass, presents itself as a viable substitute, offering significant potential to mitigate greenhouse gas emissions and enhance energy security [2]. Unlike its first-generation counterpart, which utilizes edible crop components (starch or sugar), second-generation bioethanol production leverages agricultural and forestry residues, thereby avoiding direct competition with the global food supply chain [3].

As a major agrarian nation, Indonesia's substantial food crop output results in the annual generation of massive volumes of agricultural residues [4]. These byproducts, such as rice straw, corn cobs/stalks, and sugarcane bagasse, possess a high cellulose fraction, a glucose homopolymer, that is an ideal feedstock for bioethanol synthesis [5]. Despite this potential, the majority of these residues are either incinerated or left to decompose, practices that contribute negatively to air pollution and methane release. The strategic and effective management of agricultural residues through their conversion into high-value liquid fuel (bioethanol) thus offers a dual advantage: waste management and energy diversification [6].

This investigation is designed to quantify and map the maximum theoretical conversion potential of cellulose from key national food crop residues into bioethanol. The methodology employed is a theoretical mass balance approach, which systematically integrates official national crop production data with established biochemical conversion stoichiometry parameters. While previous research has focused on assessing conversion efficiencies at the laboratory scale [7], comprehensive national-scale analyses using governmental production data to project this maximum theoretical potential remain limited. This mapping exercise is intended to furnish a data-driven roadmap for renewable energy development, offering essential quantitative insights for policymakers and investors without incurring prohibitive experimental costs.

2. Materials and Method

Research Approach and Data Sources

This study constitutes a secondary data analysis founded on theoretical mass balance calculations aimed at projecting the absolute maximum potential of bioethanol obtainable from agricultural residues. This approach fundamentally assumes 100% stoichiometric efficiency for both the hydrolysis and fermentation processes, thereby providing an estimation of the theoretical upper bound of achievable potential [8].

Official Food Crop Production Data served as the primary variable for establishing biomass availability. Production figures for major food crops (e.g., rice, corn, sugarcane) were sourced from the official publications of the Indonesian Central Bureau of Statistics (BPS). The specific data utilized are the national production totals for 2023 (BPS, 2024), representing the most recent and fully compiled data available [4].

Secondary journal data were employed to determine the specific biomass conversion parameters. These essential numerical values were compiled from authoritative, contemporary scientific literature focusing on lignocellulosic bioconversion:

- Residue to Product Ratio (RPR): The RPR value dictates the quantity of residue biomass generated per unit of harvested product. Average RPR values for rice straw, corn stover/cobs, and sugarcane bagasse were derived from reliable review studies.
- Cellulose Content: The percentage of cellulose (% dry weight) in each targeted residue type was obtained from chemical composition data reported in recent, specialized literature [9].

Theoretical Mass Balance Calculation

The calculation of bioethanol potential is based on a sequence of mass conversion steps utilizing stoichiometric factors.

Estimation of Total Residue Biomass (TR)

The total dry mass of the residue produced is calculated by multiplying the crop production data (P) by the Residue to Product Ratio (RPR):

$$TR = P \times RPR$$

Where:

- TR = Total Residue Biomass (dry tons)
- P = Major Crop Production (tons) (BPS, 2024)
- RPR = Residue Biomass Ratio (dimensionless)

Estimation of Cellulose Mass (MC)

The mass of pure cellulose within the total residue is calculated using the average cellulose content () sourced from the secondary literature:

$$MC = TR \times \%Cellulose$$

Where:

- MC = Cellulose Mass (tons)
- = Mass fraction of cellulose in dry biomass.

Estimation of Theoretical Glucose Potential (GT)

Cellulose is theoretically hydrolyzed to glucose. The stoichiometry of cellulose hydrolysis $(C_6H_{10}O_5)_n$ to glucose $nC_6H_{12}O_6$ indicates that 162 grams of cellulose requires 18 grams of water to yield 180 grams of glucose. The theoretical conversion factor ($\text{Factor}_{\text{Cel}\rightarrow\text{Glu}}$) is therefore $\frac{180}{162} \approx 1.11$

$$GT = MC \times 1.11$$

Where:

- GT = Theoretical Glucose Potential (tons)
- 1.11 = Stoichiometric cellulose-to-glucose conversion factor.

Estimation of Maximum Theoretical Bioethanol Potential (EB)

Glucose is subsequently fermented into ethanol and carbon dioxide, following the Gay-Lussac equation:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The molecular weight of glucose is 180 g/mol and ethanol is 46 g/mol. Theoretically, 180 grams of glucose produces $2 \times 46 = 92$ grams of ethanol. The stoichiometric conversion factor ($\text{Factor}_{\text{Glu}\rightarrow\text{Ethanol}}$) is $\frac{92}{180} \approx 0.511$ (Gupta & Tuohy, 2021).

$$EB = GT \times 0.511$$

Where:

- EB = Maximum Theoretical Bioethanol Potential (tons)

- 0.511 = Stoichiometric glucose-to-ethanol conversion factor.

Key Assumptions and Model Limitations

This theoretical mass balance model relies on the following key assumptions:

- Perfect Stoichiometric Conversion (100% Yield): All available cellulose is presumed to be convertible into glucose, and all glucose into ethanol. In real-world scenarios, the efficiency of the overall process (pre-treatment, enzymatic hydrolysis, and fermentation) is substantially lower [10].
- Homogeneous Composition Data: The mean cellulose composition values are assumed to be nationally representative, despite potential variations due to climatic factors, soil types, and crop cultivars.
- Total Residue Availability: The calculation posits that all generated residue is available for conversion, disregarding the necessary fraction required for soil nutrient replenishment, animal feed, or other essential purposes.

3. Result

National Production of Primary Agricultural Residues

Based on the official BPS data (2024), the total production of Indonesia's key food crops in 2023 indicated massive dry biomass potential for residues, calculated using average RPR values from the literature (Table 1). As the primary commodity, rice contributed the largest residue volume, namely rice straw.

Table 1. Estimated Total Dry Residue Biomass from Major Food Crops in 2023

Crop Type	Crop Production (10^6 Tons)	RPR (Residue/Product Ratio)	Estimated Total Residue (10^6 Dry Tons)
Rice (Padi)	54.40	1.2	65.28
Corn (Jagung)	14.70	1.0	14.70
Sugarcane (Tebu)	24.30	0.28	6.80
Total	86.78		

Note: RPR values are averages from reliable literature (Aini et al., 2021). Rice straw, corn stalks/ cobs, sugarcane bagasse (based on milled cane).

Theoretical Cellulose Content and Glucose Potential

The mass of pure cellulose within the total residue was calculated using average cellulose content obtained from the latest biomass composition studies (Table 2). Rice straw possesses a notably high cellulose content, despite the inherent difficulty in hydrolyzing lignocellulose compared to starch. Based on the mass balance calculation (Section 2.2), the theoretical glucose potential was determined using the cellulose-to-glucose conversion factor (1.11).

Table 2. Estimated Cellulose Mass and Theoretical Glucose Potential

Residue Type	Total Residue (10^6 Dry Tons)	% Cellulose (w/w)	Cellulose Mass (10^6 Tons)	Theoretical Glucose Potential (10^6 Tons)
Rice Straw	65.28	38.0	24.81	27.54
Corn Residue	14.70	40.0	5.88	6.53
Sugarcane Bagasse	6.80	42.0	2.86	3.17
Total	86.78	33.55	37.24	37.15

Note: % Cellulose values are average mass fractions of dry weight (Sarkar et al., 2020). Rice straw. Corn residue (cobs and stalks). Sugarcane bagasse.

Mapping of Theoretical Bioethanol Potential

The maximum theoretical bioethanol conversion potential was calculated using the theoretical glucose potential and the stoichiometric glucose-to-ethanol conversion factor (0.511). This result represents the peak potential achievable under ideal, 100% efficiency conditions, serving as the theoretical upper limit (Gong et al., 2021). The total bioethanol potential from these three residues collectively reaches 19.03 million tons per year (Table 3).

Table 3. Maximum Theoretical Bioethanol Potential from Agricultural Residues

Residue Type	Theoretical Glucose Potential (10^6 Tons)	Glu → Ethanol Conversion Factor	Maximum Theoretical Bioethanol Potential (10^6 Tons)
Rice Straw	27.54	0.511	14.07
Corn Residue	6.53	0.511	3.34
Sugarcane Bagasse	3.17	0.511	1.62
Total	37.24		19.03

To convert the mass potential (tons) into volume (Liters), the density of anhydrous ethanol is used, which is 0.789 g/cm^3 at 20°C (Gupta & Tuohy, 2021).

$$Volume\ (L) = \frac{Massa\ (ton) \times 10^6}{\text{Density}\ (kg/L)}$$

With a density of 0.789 kg/L, the maximum total theoretical bioethanol potential is:

$$Volume_{total} = \frac{19.03 \times 10^6 \text{ tons} \times 1000 \text{ kg/ton}}{0.789 \text{ kg/L}} \approx 24.12 \times 10^9 \text{ Liters}$$

The Maximum Theoretical Bioethanol Potential yielded from the cellulose of primary agricultural residues is approximately 24.12 Billion Liters annually.

Sensitivity Analysis: Impact of Process Efficiency

Acknowledging that the 100% potential is an ideal scenario, a sensitivity analysis based on actual conversion efficiency is critical. In pilot and small-scale studies, the overall conversion efficiency from cellulose to ethanol typically ranges between 40% and 60% of the theoretical maximum [10].

If a conservative overall actual conversion efficiency of 50% is assumed, the realistic bioethanol potential is 50% of the maximum theoretical potential.

$$EB_{\text{Actual}} = EB_{\text{Maximum}} \times 0.50$$
$$EB_{\text{Actual}} = 24.12 \times 10^9 \text{ Liters} \times 0.50 \approx 12.06 \times 10^9 \text{ Liters}$$

Even at a conservative 50% conversion efficiency, the potential bioethanol from agricultural residues still amounts to approximately 12.06 Billion Liters per year.

4. Discussion

Interpretation of Results and Significance

The maximum theoretical bioethanol potential of 24.12 Billion Liters per year from agricultural cellulose residues (rice, corn, sugarcane) indicates that Indonesia possesses immense biomass resources for an energy transition. Rice straw is the dominant contributor, accounting for over 70% of the total potential, which aligns with rice's prevailing role in national food crop production [4]. This result emphatically highlights the necessity of an integrated strategy for managing rice residue that goes beyond current common and inefficient practices like field burning or minimal soil incorporation [6].

The 24.12 Billion Liters/year figure represents the theoretical upper limit and serves as a crucial benchmark for evaluating the nation's total resource capacity. When juxtaposed with national gasoline consumption, this potential could significantly diminish dependence on crude oil imports and enhance domestic energy independence. Even with a more pragmatic actual conversion efficiency (e.g., 50%, yielding 12.06 Billion Liters), the quantity still signifies a substantial and untapped reserve of renewable energy.

Theoretical and Practical Implications

Theoretically, this study validates the mass balance methodology for large-scale biomass resource mapping. This approach offers a robust planning tool for governmental bodies or institutions seeking to pinpoint strategic locations for the establishment of second-generation bioethanol production clusters. By meticulously integrating official BPS production data with established conversion parameters from the literature, this research achieves a higher degree of spatial-temporal precision compared to general global estimations.

Practically, the paramount challenge in realizing this potential is the inherent complexity of lignocellulose conversion. The rigid, protective structure of lignocellulose (the lignin matrix) necessitates expensive and energy-intensive pre-treatment, followed by enzymatic hydrolysis which remains a high-cost component, prior to effective fermentation. Innovations in cost-effective pre-treatment methods and the development of more robust and tolerant enzymes/microorganisms (such as genetically modified Saccharomyces cerevisiae) are critical to bridge the gap between the actual yield and the 51.1% theoretical maximum [7].

Comparison with Prior Studies

Earlier studies often concentrated on the bioethanol potential of a single biomass type or were geographically restricted to regional scales [5]. For instance, Aini et al.'s (2021) research demonstrated considerable conversion potential at the sub-national level, but national aggregation often lacked a clear and up-to-date foundation of official data. This study addresses that gap by leveraging the most recent and officially verified BPS (2024) data as its core foundation.

Methodologically, the utilization of 1.11 for hydrolysis and 0.511 for fermentation conversion factors is consistent with established bioconversion literature. However, it is essential to note that the % cellulose values (e.g., 38.0% for rice straw) can be variable. This research utilized an average value derived from systematic reviews, which, while not capturing extreme field variability, provides the most representative estimate for a national-scale assessment.

A further challenge lies in sustainability. Not all residues can or should be diverted for energy production. A portion of the residue must be returned to the soil to maintain fertility and nutrient balance. Consequently, the actual technically recoverable potential will inevitably be lower than the theoretical potential mapped in this study.

5. Conclusions

Main Conclusions

This study successfully mapped the conversion potential of cellulose from major agricultural residues (rice, corn, sugarcane) in Indonesia into bioethanol using a theoretical mass balance approach and official national production data (BPS, 2024).

The national Maximum Theoretical Bioethanol Potential is approximately 24.12 Billion Liters per annum, with rice straw being the overwhelming contributor (>70%). This figure represents a theoretical upper limit, signifying an abundant and underutilized lignocellulosic biomass resource. Even at a realistic conversion efficiency of 50%, the bioethanol potential remains around 12.06 Billion Liters per year, providing a strong basis for national energy diversification programs.

Research Limitations

The results presented are the theoretical potential and do not reflect actual yields in conversion plants, as the model assumes 100% process efficiency. Other major limitations include:

- Compositional Data Accuracy: The reliance on average cellulose content values may not fully account for regional variations stemming from soil, climate, and specific agricultural practices.
- Technical Availability: The model does not factor in the mandatory fraction of residue that must remain in the field to preserve soil quality and prevent erosion, or that is reserved for animal feed.
- Process Bottlenecks: The model overlooks the technical difficulties and high costs associated with biomass pre-treatment, which represent the foremost constraint in industrial-scale lignocellulose conversion.

Suggestions and Recommendations

- Further Research: Future work should focus on a technical and economic mass balance study that integrates this potential data with specific pre-treatment costs and the actual yield efficiency of various conversion technologies (e.g., Dilute Acid Hydrolysis vs. Organosolv).
- Energy Roadmap: The government should utilize this potential mapping to formulate a national renewable energy roadmap, prioritizing the development of second-generation bioethanol industrial clusters in key rice and sugarcane production centers.
- Technological Innovation: Continued investment in research and development of cheaper, environmentally benign biomass pre-treatment technologies is crucial to close the existing gap between the high theoretical potential and the current low actual conversion yield.

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