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BIOENERGY POTENTIAL ASSESSMENT BASED ON AGRICULTURAL CROP RESIDUES IN THE EAST ZANGEZUR ECONOMIC REGION, AZERBAIJAN

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ABSTRACT

Rapid growth in energy demand and increasing environmental concerns have strengthened interest in agricultural crop residues as a renewable energy resource. This study assessed the bioenergy potential of agricultural crop residues in Azerbaijan's East Zangezur Economic Region using official 2024 agricultural production data and the FAO Bioenergy and Food Security (BEFS) Rapid Appraisal framework. We used a deterministic, scenario-based assessment pathway that integrated crop-production data, crop-specific or representative residue-to-product ratios (RPRs), residue-availability coefficients, lower heating values (LHVs), and electrical conversion efficiency. To avoid double counting, we separated wheat from the aggregated "cereals and pulses" statistical category and calculated the remaining production of other cereals and pulses separately. We estimated total gross crop-residue production at 24,508.70 t/year, of which approximately 4,686.04 t/year was classified as scenario-available for bioenergy production after applying crop-specific or representative availability coefficients. The corresponding theoretical energy potential was approximately 22.80 GWh/year. Applying an adopted electrical conversion efficiency of 25% resulted in an estimated electricity-generation potential of approximately 5.70 GWh/year. Wheat and other cereals and pulses were the dominant contributors, together accounting for approximately 71.5% of the total estimated electricity-generation potential. Under a grid-displacement scenario using an emission factor of 0.4066 t CO_2/MWh, the estimated electricity generation could avoid approximately 2.32 kt CO_2-eq/year. However, these estimates are scenario-based technical estimates, not practical or economically recoverable biomass. The results indicate that agricultural crop residues could provide a modest but environmentally relevant contribution to renewable-energy development in East Zangezur Economic Region.

Keywords: Agricultural crop residues, Bioenergy potential, Biomass, BEFS Rapid Appraisal, Greenhouse gas emissions.

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1. INTRODUCTION

As globalization expands international economic relations, living standards rise, and the global population grows, energy security issues are becoming increasingly acute. Although existing hydrocarbon reserves can currently meet global energy demand, their rapid depletion could threaten global energy security within the next 40–50 years. Anthropogenic environmental challenges, particularly climate change, further underscore the need to expand the use of alternative energy sources (Zhang et al., 2023; Sadigov et al., 2025). In this context, technological advances in renewable energy production from sources such as solar, wind, and biomass are particularly significant (De Wit & Faaij, 2010).

Converting agricultural waste into bioenergy reduces environmental risks, enhances energy security, supports sustainable waste management, and ensures access to clean, affordable, and reliable energy sources (Sadigov & Macnunlu, 2023). Applying innovative technologies to monitor feedstock pretreatment, optimize conversion parameters, and measure bioenergy output can further improve the efficiency and sustainability of bioenergy production and utilization systems (Awogbemi et al., 2024). Recent global assessments also show that agricultural

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biomass plays an important role in the transition toward a circular, low-carbon bioeconomy. However, the usable potential of crop residues depends not only on the amount generated but also on technical, environmental and socio-economic constraints that determine whether residues can be sustainably mobilized (Antar et al., 2021; Ezealigo et al., 2021; Singh et al., 2022).

IRENA (2023) emphasizes that agricultural-residue assessments should account for agronomic constraints, competing uses, collection systems, and local conditions rather than treating all generated biomass as freely recoverable. This distinction is important when differentiating theoretical residue potential from scenario-based technical potential. Given the projected increase in the global population to 10 billion by 2050, global agricultural production and the annual generation of millions of tons of renewable residues are expected to rise accordingly. The future integration of bioproducts derived from agricultural waste into agro-industrial systems may reduce waste generation, enhance resource-use efficiency and sustainability across the entire value chain, and promote the development of a circular economy by minimizing environmental impacts while improving agricultural productivity (Díaz et al., 2023; Akter et al., 2024; Groff et al., 2025; Ullah et al, 2025).

At the same time, sustainable residue utilization must be balanced against soil and agricultural requirements. Crop residues retained in the field contribute to nutrient recycling, moisture conservation, erosion protection, maintenance of soil organic matter, and long-term soil productivity. Recent studies have demonstrated that excessive residue removal may negatively affect soil organic carbon and soil quality (Alvarez, 2024; Díaz et al., 2024). Crop-residue management studies also emphasize that retention, incorporation, mulching, and other on-farm uses should be considered before residues are allocated to energy production (Shinde et al., 2022; Kumar et al., 2023; Dey et al., 2024; Osman et al., 2024).

The socio-economic implications of biomass utilization are not uniformly positive. High investment and capital costs, technological maturity of biofuels, large-scale biomass supply, and regulatory and policy issues represent key challenges. Nevertheless, with appropriate strategies and solutions, complete valorization of biomass is achievable (Zhang et al., 2021; Raina et al., 2024; Todde et al., 2025; Zimmer et al., 2025).

In addition to economic factors, residue-to-product ratios (RPRs), residue-availability coefficients, lower heating values (LHVs) and conversion efficiency strongly influence calculated bioenergy potential. Applying crop-specific or representative parameters is therefore preferable to applying a single uniform coefficient across heterogeneous agricultural residues (Fartash Naeimi et al., 2023; Sarkar et al., 2023; Díaz et al., 2024).

Recent field-based studies have also demonstrated that generalized assumptions regarding residue availability may substantially overestimate the amount of biomass that can actually be mobilized (Shahzad et al., 2024; Pawaiya et al., 2025; Murmu et al., 2025). Kapoor et al. (2023), for example, reported that field-survey-based estimates of crop-residue availability were considerably lower than earlier generalized estimates. This reinforces the need to distinguish gross residue generation from technically and sustainably available biomass.

Recent reviews further indicate that thermochemical conversion routes differ substantially in feedstock requirements, operating conditions, preprocessing needs, conversion efficiency, and environmental performance. Consequently, the same quantity of agricultural residue may produce substantially different useful-energy outputs depending on the selected technology and system configuration (Paudel et al., 2024; Sikiru et al., 2024; Sattar et al., 2025).

The energy contained in biomass should not be interpreted as equivalent to useful electricity output. Actual electricity generation depends on the efficiency of the selected conversion technology, plant scale, biomass moisture content, preprocessing requirements, and operating conditions. Therefore, theoretical energy potential and electricity-generation potential should be reported separately (Morrone et al., 2022; Järvinen et al., 2025). Spatial and logistical conditions represent another important limitation. Agricultural residues are often seasonally available and geographically dispersed, while collection distance, road access, storage, preprocessing, and biomass density can substantially affect the amount that is practically recoverable. GIS-based approaches are increasingly used to integrate agricultural-production data with terrain, land use, infrastructure, residue density, and transportation constraints (Lovrak et al., 2020; Zhang et al., 2021; Siegrist et al., 2022; Wang et al., 2023; Fartash Naeimi et al., 2025). Transportation itself can represent a major component of biomass supply-chain costs and environmental impacts, particularly for low-density and spatially dispersed residues (Wang et al., 2021; Roudneshin & Sosa, 2024).

Agricultural-residue bioenergy is also relevant for Azerbaijan. A national-scale assessment demonstrated that crop residues can contribute to the country's bioenergy resource base (Fartash Naeimi et al., 2023). However, national estimates cannot fully reflect conditions within individual economic regions because crop composition, cultivated area, production volume, environmental conditions, and residue availability vary spatially.

The East Zangezur Economic Region is particularly important in this context because of its agricultural-development potential and considerable variation in natural conditions, elevation, soils, vegetation, and agricultural land resources. Previous research has identified significant natural-ecological and agricultural potential in the region (Mammadov et al., 2025). Despite previous national assessments of agricultural-residue bioenergy in Azerbaijan,

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region-specific quantitative information for East Zangezur remains limited. In particular, the study area lacks an integrated assessment that combines recent regional crop-production data with crop-specific or representative RPRs, residue-availability coefficients, LHVs, electricity-conversion efficiency, and greenhouse-gas displacement. This study addresses this gap by applying the FAO Bioenergy and Food Security (BEFS) Rapid Appraisal framework to assess the bioenergy potential of agricultural crop residues in the East Zangezur Economic Region, using official 2024 agricultural production data. The study's novelty lies in integrating regional crop-production statistics with crop-specific or representative RPRs, residue-availability coefficients, LHVs, a defined electricity-conversion efficiency, and a grid-displacement GHG scenario into one internally consistent calculation pathway.

Accordingly, the objectives of the study are to: (i) quantify annual crop-residue generation from the major agricultural crops of the East Zangezur Economic Region; (ii) estimate scenario-available biomass using crop-specific or representative residue-availability coefficients; (iii) calculate the theoretical energy potential of the available biomass using appropriate LHVs; (iv) estimate electricity-generation potential under a defined conversion-efficiency scenario; and (v) estimate the potential greenhouse-gas reduction associated with displacement of electricity from the national grid. The assessment is deterministic and scenario-based and should therefore be interpreted as a regional screening estimate rather than a prediction of guaranteed field-scale biomass supply or electricity generation.

2. MATERIALS AND METHODS

2.1. The Object of Research

The study was conducted in the East Zangezur Economic Region of Azerbaijan, located within the Lesser Caucasus and covering approximately 744,800 ha (Fig. 1). The economic region comprises the administrative districts of Zangilan, Gubadli, Jabrayil, Lachin, and Kalbajar (Mammadov et al., 2025). The study area is characterized by considerable topographic variation, with elevations ranging from approximately 160 to 3,681 m above sea level. Elevation generally decreases from the northwestern mountainous areas toward the southeastern lowlands. The Digital Terrain Model (DTM) used to characterize regional topography was developed using publicly available elevation data from the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM). Satellite imagery and existing topographic maps were additionally used to support terrain representation (Mammadov et al., 2025) (Fig. 2).



Fig. 1: Location of the East Zangezur Economic Region in Azerbaijan.

The soil cover of the East Zangezur Economic Region can be characterized as follows: the high-mountain zone contains various subtypes of mountain-meadow soils; the mid-mountain zone is dominated by brown mountain-forest soils; the mid- and low-mountain areas feature mountain-chernozem and mountain gray-brown soils; and the foothills and plains exhibit a variety of gray-brown soils, gray soils, gray-meadow soils, and alluvial-meadow soils (Yusifova & Alizade, 2025a). These geographical conditions are relevant to the assessment because terrain, agricultural distribution, and infrastructure may influence future residue collection, transportation, and practical biomass utilization.

2.2. Study Design, Scope and Data Sources

The study employed a deterministic, scenario-based assessment approach to estimate the crop-residue bioenergy potential of the East Zangezur Economic Region. Official agricultural production and cultivated-area data referring to 2024 were obtained from the State Statistical Committee of the Republic of Azerbaijan and reported in the 2025 edition of the Agriculture of Azerbaijan (State Statistical Committee of the Republic of Azerbaijan, 2024). The quantitative assessment considered the following crop categories: wheat; other cereals and pulses; sugar beet; sunflower; potato; vegetables; melon crops; fruits and berries; grapes. The study focused exclusively on agricultural crop residues. Livestock manure, forest residues, municipal solid waste, wastewater, biogas production, syngas production, and other biomass pathways were outside the defined scope.

A methodological issue arose because wheat is already included within the official statistical category “cereals and pulses (total)”. To avoid double counting, the quantity attributed to other cereals and pulses was calculated as:

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$$P(other\ cereals\ and\ pulses)=P(cereals\ and\ pulses,total)-Pwheat \quad (1)$$

Using the official 2024 production data:

$$P(other\ cereals\ and\ pulses)=39{,}507.2-31{,}000.5 P(other\ cereals\ and\ pulses)=8{,}506.7\ t/year$$

Therefore, the subsequent calculations used:

$Pwheat$=31,000.5 $t/year$ and

$P(other\ cereals\ and\ pulses)$=8,506.7 $t/year$

as mutually exclusive production categories.

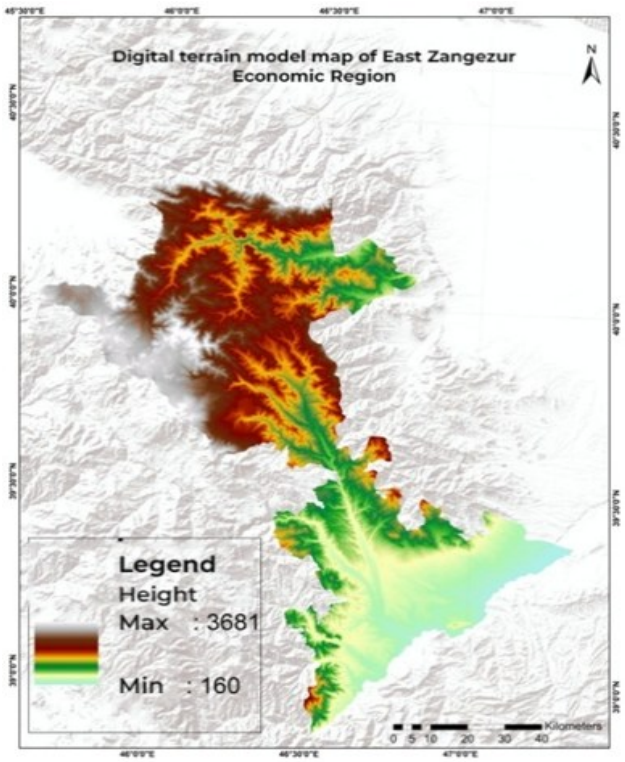


Fig. 2: Digital Terrain Model of the East Zangezur Economic Region based on SRTM and ASTER GDEM elevation data (Mammadov et al., 2025).

2.3. BEFS Methodological Framework

The assessment was conducted according to the general principles of the Bioenergy and Food Security Rapid Appraisal (BEFS RA) framework developed by the Food and Agriculture Organization of the United Nations (FAO, 2014).

The present study applied the agricultural crop-residue resource-assessment component of the BEFS framework. The total quantity of agricultural residues generated cannot automatically be considered available for energy production because part of the residue may need to remain within the agricultural system to support nutrient cycling, soil organic matter, moisture conservation, erosion protection, and other agronomic functions. Additional quantities may also have competed agricultural or non-energy uses.

Conceptually, crop-residue availability was expressed as:

$$CR_{available} = CR_{total} - CR_{soil} - CR_{other} \quad (2)$$

where:

$CR_{available}$ - crop residues potentially available for bioenergy production (t/year);

CR_{total} - total crop residues generated annually (t/year);

CR_{soil} - residues retained for soil protection and agronomic functions (t/year);

CR_{other} - residues allocated to competing non-energy uses (t/year).

Because field-specific measurements of soil-retention requirements and competing uses were unavailable for all crop categories in East Zangezur, this conceptual relationship was operationalized using crop-specific or representative residue-availability coefficients derived from published literature. IRENA (2023) emphasizes that technical agricultural-residue potential should consider agronomic restrictions, competing uses, collection systems, and local conditions rather than treating all generated biomass as freely recoverable.

2.4. Selection of RPR, Residue-availability and LHV Parameters

Crop-residue generation was estimated using residue-to-product ratios (RPRs). RPR represents the mass of residue generated per unit mass of harvested agricultural product. Because residue generation, recoverability, and energy characteristics differ among crops, crop-specific or representative values were applied rather than using one universal coefficient. Lower heating value (LHV) was used to estimate the energy contained in the scenario-available biomass. LHV values were expressed in MJ/kg.

For aggregated crop categories where detailed crop composition was unavailable, representative literature-based crop residues were used as proxies. These parameters were treated as scenario parameters and as a source of methodological uncertainty (Table 1).

For wheat, potato, melon crops, sugar beet, and the barley-straw proxy, the RPR, availability, and LHV parameters were adopted from Fartash Naeimi et al. (2023). For sunflower stalks, an RPR of 0.60, availability coefficient of 60%, and LHV of 14.20 MJ/kg were adopted from Gedik et al. (2023). For vegetables, tomato pruning was used as a representative proxy. An RPR of 0.41 and LHV of 15.29 MJ/kg were adopted from Díaz et al. (2024). Because locally measured residue-recovery data were unavailable, an availability coefficient of 50% was adopted as a screening-level scenario parameter. For fruits and berries, apple pruning was used as a representative proxy, while grapevine pruning was applied to grapes. These values were treated as representative parameters rather than field-measured regional coefficients.

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Table 1: Input parameters used for crop-residue and bioenergy assessment

Crop category	Representative residue	RPR	Availability (%)	LHV (MJ/kg)	Source / methodological note
Wheat	Straw	0.45	15	17.90	Fartash Naeimi et al. (2023)
Other cereals and pulses	Barley-straw proxy	0.95	15	17.50	Fartash Naeimi et al. (2023); proxy
Sugar beet	Crop residue	1.00	50	17.21	Fartash Naeimi et al. (2023)
Sunflower	Stalk	0.60	60	14.20	Gedik et al. (2023)
Potato	Haulm/residue	0.10	50	15.34	Fartash Naeimi et al. (2023)
Vegetables	Tomato-pruning proxy	0.41	50	15.29	RPR and LHV: Díaz et al. (2024); availability adopted as scenario parameter
Melon crops	Crop residue	0.15	50	20.50	Fartash Naeimi et al. (2023)
Fruits and berries	Apple-pruning proxy	0.30	80	18.05	Fartash Naeimi et al. (2025)
Grapes	Grapevine pruning	0.30	80	16.37	Fartash Naeimi et al. (2025)

2.5. Estimation of Gross and Scenario-available Crop Residues

The gross annual amount of crop residue was calculated as:

$$R_i = P_i \times RPR_i \quad (3)$$

Where:

R_i - gross crop-residue production for crop i (t/year);
P_i - annual production of crop i (t/year);
RPR_i - residue-to-product ratio of crop i.

The scenario-available residue was subsequently calculated as:

$$R_{(a,i)} = R_i \times A_i \quad (4)$$

Where:

$R_{(a,i)}$ - scenario-available residue for crop i (t/year);
R_i - gross residue production (t/year);
A_i - crop-specific availability coefficient expressed as a decimal.
Availability coefficients of 15, 50, 60, and 80% were entered as: 0.15, 0.50, 0.60, and 0.80, respectively.

Worked calculation for wheat

Annual wheat production: $P_{wheat} = 31{,}000.5\ t/year$

RPR:
RPR_{wheat}=0.45

Gross wheat residue: $R_{wheat} = 31{,}000.5 \times 0.45 R_{wheat} = 13{,}950.225\ t/year$
Rounded:
R_{wheat}=13,950.23 t/year
The availability coefficient for wheat was:
A_{wheat}=0.15
Therefore: $R(a, wheat) = 13{,}950.225 \times 0.15 R_{(a,wheat)} = 2{,}092.53375\ t/year$
Rounded: Thus, approximately 2,092.53 t/year of wheat straw was classified as scenario-available for bioenergy production.

The same procedure was applied to all other crop categories.
The total gross and scenario-available residue quantities were calculated as:

$$R_{(gross,total)} = \sum R_i \quad (5)$$

and:

$$R_{(available,total)} = \sum R_{(a,i)} \quad (6)$$

Using unrounded intermediate values:

$$R_{(gross,total)} = 24{,}508.70\ t/year$$

$$R_{(available,total)} = 4{,}686.04\ t/year$$

These quantities represent scenario-based technical residue potential, rather than practically or economically recoverable biomass.

2.6. Estimation of Theoretical Energy Potential

The theoretical energy content of scenario-available crop residues was calculated using crop-specific or representative LHV values.

The energy potential of each crop residue was calculated as:

$$E_{(th,i)} = R_{(a,i)} \times 1000 \times LHV_i \quad (7)$$

Where:

$E_{(th,i)}$ = theoretical energy potential of crop residue i (MJ/year);
$R_{(a,i)}$ = scenario-available residue (t/year);
1000 = conversion factor from tonnes to kilograms;

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LHV_i = lower heating value (MJ/kg).

Energy was converted from MJ/year to MWh/year using:

$$E_{(th,MWh)} = E_{(th,MJ)}/3600 \quad (8)$$

because: $1\ MWh = 3600\ MJ$

Worked calculation for wheat

Available wheat residue: $R_{(a,wheat)} = 2{,}092.53375\ t/year$

LHV: $LHV_{wheat} = 17.90\ MJ/kg$

Therefore: $E_{(th,wheat)} = 2{,}092.53375 \times 1000 \times 17.90 E_{(th,wheat)} = 37{,}456{,}354.125\ MJ/year$

Conversion to MWh: $E_{(th,wheat,MWh)} = 37{,}456{,}354.125/3600$

$E_{(th,wheat,MWh)} = 10{,}404.54\ MWh/year$

or: $E_{(th,wheat)} = 10.40\ GWh/year$

The total theoretical energy potential was calculated as:

$$E_{(th,total)} = \sum E_{(th,i)} \quad (9)$$

Using unrounded intermediate values:

$$E_{(th,total)} = 82{,}094{,}621.91\ MJ/year$$

Therefore:

$$E_{(th,total)} = 82{,}094{,}621.91/3600 E_{(th,total)} = 22{,}804.06\ MWh/year$$

2.7. Estimation of Electricity-generation Potential

Only part of the theoretical energy contained in biomass can be converted into useful electrical energy. An electrical conversion efficiency of 25% was adopted for the baseline scenario. Traditional biomass-fired steam power plants have been reported to have average electrical efficiencies close to 25% (Morrone et al., 2022).

Electricity-generation potential was calculated as:

$$E_{(el,i)} = E_{(th,i)} \times \eta \quad (10)$$

where:

$E_{(el,i)}$ - electricity-generation potential;

$E_{(th,i)}$ -theoretical energy potential;

η = electrical conversion efficiency.

For the present assessment:

η =0.25

Therefore:

$$E_{(el,MWh)} = E_{(th,MWh)} \times 0.25$$

Worked calculation for wheat

Theoretical energy: $E_{(th,wheat)} = 10{,}404.54\ MWh/year$

Therefore:

$$E_{(el,wheat)} = 10{,}404.54 \times 0.25 E_{(el,wheat)} = 2{,}601.14\ MWh/year$$

The total electricity-generation potential was calculated as:

$$E_{(el,total)} = \sum E_{(el,i)} \quad (11)$$

or:

$$E(el,total) = 22{,}804.06 \times 0.25$$
$$E(el,total) = 5{,}701.02\ MWh/year$$

The calculated electricity potential represents a scenario-based estimate and should not be interpreted as guaranteed electricity production from a future operating facility.

2.8. Greenhouse Gas Emission-reduction Scenario

The potential greenhouse gas benefit was estimated using a grid-displacement approach, assuming that electricity generated from crop residues replaces an equivalent quantity of electricity supplied by the Azerbaijan electricity grid. The annual potential emission reduction was calculated as:

$$GHG_{red} = E_e l \times EF_{grid} \quad (12)$$

where:

GHG_{red}- potential greenhouse gas emission reduction (t CO_2-eq/year);

E_{el} - electricity-generation potential (MWh/year);

EF_{grid} - electricity-grid emission factor (t CO_2/MWh).

The adopted electricity-grid emission factor was:

$$EF_{grid} = 0.4066\ t\ CO_2/MWh \quad (13)$$

This value represents the combined-margin grid emission factor reported in recent Azerbaijan electricity-sector project documentation (AzerEnerji OJSC & SOCAR Trading SA, 2025).

The combined-margin factor was calculated as:

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$$EF_{(grid,CM)} = 0.50 \times 0.4497 + 0.50 \times 0.3634$$
$$EF_{(grid,CM)} = 0.40655$$

Rounded:

$$EF_{(grid,CM)} = 0.4066\ t\ CO_2/MWh$$

Worked calculation for wheat
Electricity-generation potential:

$$E_{(el,wheat)} = 2{,}601.14\ MWh/year$$

Therefore:

$$GHG_{(red,wheat)} = 2{,}601.14 \times 0.4066$$

$$GHG_{(red,wheat)} = 1{,}057.62\ t\ CO_2 - eq/year$$

Total GHG Reduction

$$GHG_{(red,total)} = 5{,}701.02 \times 0.4066$$

$$GHG_{(red,total)} = 2{,}318.03\ t\ CO_2 - eq/year$$

or approximately:

$$GHG_{(red,total)} = 2.32\ kt\ CO_2 - eq/year$$

The calculated value represents a gross grid-displacement potential, rather than a complete life-cycle greenhouse gas balance. It does not deduct emissions from harvesting, collection, transportation, drying, storage, preprocessing, plant construction, facility operation, or auxiliary energy consumption.

2.9. Methodological Uncertainty and Limitations

The estimated crop-residue bioenergy potential is subject to uncertainty associated with agricultural-production statistics, residue-to-product ratios, residue-availability coefficients, lower heating values, and electricity-conversion efficiency. These parameters may vary according to crop variety, climatic conditions, agricultural practices, harvesting technology, biomass moisture content, and local management conditions. Additional uncertainty arises from aggregated statistical categories, particularly “other cereals and pulses”, “vegetables”, and “fruits and berries”. Because detailed crop composition was unavailable, representative literature-based proxies were used. Consequently, estimates for these categories should be interpreted with greater caution than those based on directly matched crop-specific parameters.

The assessment did not explicitly model harvesting and collection losses, seasonal biomass availability, road accessibility, transportation distance, storage losses, moisture variation, competing residue uses, spatial biomass density, plant location, or technology-specific economic performance. These factors may reduce the quantity of biomass that can ultimately be recovered and converted into energy. The GHG assessment represents a grid-displacement scenario rather than a full life-cycle assessment. Therefore, emissions associated with harvesting machinery, collection, transportation, preprocessing, storage, plant construction, and facility operation were not deducted. No probabilistic uncertainty analysis was performed. Accordingly, the results should be interpreted as a deterministic, scenario-based regional screening assessment rather than field-validated biomass supply or guaranteed electricity production. Future research should combine field-based residue measurements with sensitivity analysis, GIS-based biomass-logistics assessment, technology-specific techno-economic evaluation, and life-cycle assessment to determine the practically and economically recoverable bioenergy potential of East Zangezur.

3. RESULTS

3.1. Estimation of the Bioenergy Potential from Crop Residues for the East Zangezur Economic Region

The utilization of bioenergy in agriculture is primarily based on crop and livestock production, promoting the adoption of an integrated bioenergy production model that encompasses crop cultivation, animal husbandry, and bioenergy generation. However, the precise contribution of such integrated systems to mitigating the various environmental pressures associated with crop and livestock production remains unclear. The alarming increase in global reliance on fossil fuels, such as coal, oil, and natural gas, has led to the depletion of these resources. Rapid industrialization and population growth have substantially increased energy demand. Access to clean and environmentally sustainable energy is critical for the sustainable development of human society and to meet this continuously rising demand (Yusifova & Alizade, 2025b). Biomass represents a promising alternative source for the production of clean energy. Among the most viable renewable energy options for creating a more sustainable energy system is the utilization of plant-based residues.

The East Zangezur Economic Region is a major agricultural area that plays an important role in Azerbaijan’s economy. Favorable soil and climatic conditions have created extensive opportunities for agricultural development in the region. Prior to occupation, various agricultural sectors were well developed in this region, including grain cultivation, viticulture, tobacco farming, fodder production, potato cultivation, vegetable growing, cotton production, and livestock farming (Valiyev, 2020). To estimate the bioenergy production potential from crop residues in the East Zangezur Economic Region, the study first considered the level of agricultural development and its main trends.

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Using data from the State Statistical Committee, we analyzed agricultural land use in the region. The results were used to generate charts showing how land resources are allocated to different crops across the economic region (Fig. 3).

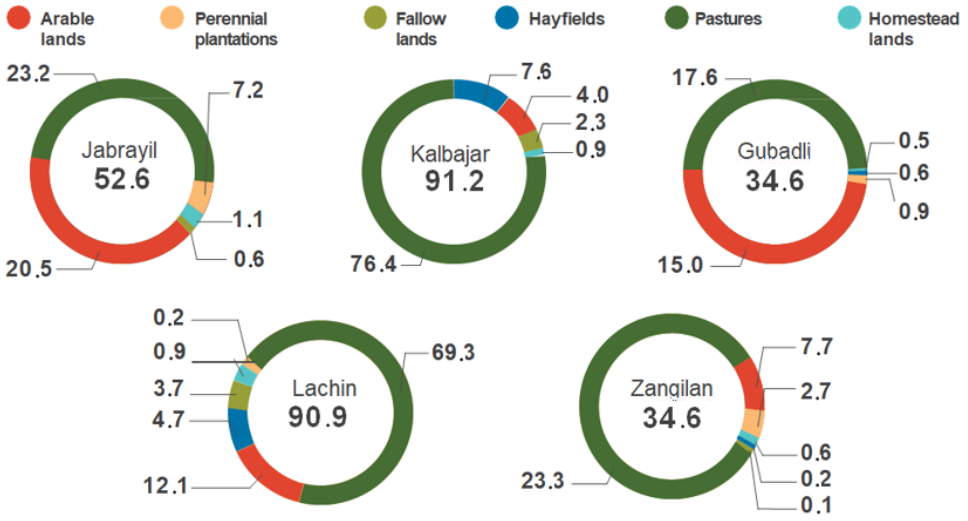


Fig. 3: The distribution of land resources across the East Zangezur Economic Region (Mammadov et al., 2025).

As shown in the charts, livestock production in the study area is more developed than crop farming: pastures and enclosures cover 209.8 thousand ha, whereas arable land is 3.5 times smaller, totaling 59.3 thousand ha. The largest cultivated areas are in the Jabrayil (20.5 thousand ha) and Gubadli (15.0 thousand ha) districts. The area under perennial crops is very limited, at only 11 thousand ha, and the Jabrayil district has the highest share of both perennial crops (7.2 thousand ha) and arable land (20.5 thousand ha) (State Statistical Committee of the Republic of Azerbaijan, 2024).

According to data from the Center for Agricultural Research under the Ministry of Agriculture of the Republic of Azerbaijan, in the post-liberation period, the largest sowing areas in the East Zangezur Economic Region are planned for cereal crops (21,800 ha), with 6,500 hectares allocated for fruits and berries and 1,400 hectares for potatoes, vegetables, and melons. Using the same data, we also prepared a chart showing projected agricultural production in the East Zangezur Economic Region (Fig. 4) (Mammadov et al., 2025). The projections indicate that the study area's arable land could yield about 70,000 tons of cereals, 11,900 tons of vegetables, and 8,400 tons of potatoes. On lands allocated to perennial crops, the expected harvest includes 46,300 tons of fruits and berries and 27,300 tons of grapes.

3.2. Agricultural Production and Statistical Treatment of Crop Categories

Currently, cereals, particularly wheat, dominate the cropping structure in the East Zangezur Economic Region as of 2024, in both sown area and total production volume. Simultaneously, high yields of potatoes and vegetables indicate the effectiveness of irrigation systems and agronomic practices. Although sugar beet yields are relatively high, the area under cultivation remains limited. Areas allocated to fruit and viticulture crops have expansion potential, but their current yields remain at an average level. Overall, improving crop yields remains a primary priority to increase agricultural production in the region.

Official agricultural statistics for 2024 showed that cereals and pulses represented the dominant crop group in the East Zangezur Economic Region, with a total annual production of 39,507.2 t/year. Wheat accounted for 31,000.5 t/year of this total. The agricultural production data used in the present assessment were obtained from the State Statistical Committee of the Republic of Azerbaijan and reported in the 2025 edition of The Agriculture of Azerbaijan (Table 2) (State Statistical Committee of the Republic of Azerbaijan, 2024).

To prevent double counting, production of cereals and pulses other than wheat was calculated as:

$$P_{(other\ cereals\ and\ pulses)} = 39{,}507.2 - 31{,}000.5 = 8{,}506.7\ t/year$$

Accordingly, 31,000.5 t/year of wheat and 8,506.7 t/year of other cereals and pulses were used as separate and mutually exclusive categories in all subsequent calculations.

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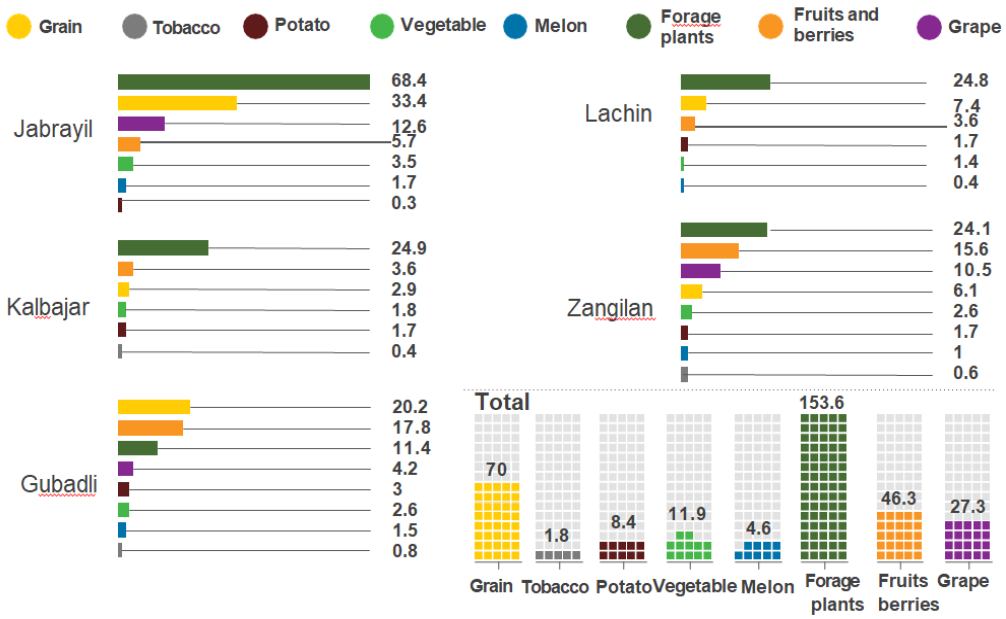


Fig. 4: The projected agricultural production in the East Zangezur Economic Region (Mammadov et al., 2025).

Table 2: Major agricultural crops in the East Zangezur Economic Region in 2024

Crops	Annual production (t/year)	Cultivated area (ha)	Productivity (t/ha)
Cereals and pulses (total)	39,507.2	32,774.4	1.21
Wheat (winter and spring)	31,000.5	29,286.8	1.06
Sugar beet	1,424.9	159.9	16.5
Sunflower (for grain)	33.0	30.0	1.10
Potato	622.5	39.2	15.88
Vegetables	1,214.5	92.5	15.67
Melon crops	19.9	6.1	3.26
Fruits and berries	1,326.5	294.0	4.51
Grapes	237.6	35.7	5.90

Note: Wheat is already included within the official statistical category "cereals and pulses (total)". Therefore, these two values were not treated as independent categories in the bioenergy calculations.

3.3. Gross and Scenario-available Crop Residues

The assessment of crop residue generation and their suitability for bioenergy production was conducted using the BEFS Rapid Appraisal methodological approach.

Gross crop-residue generation was estimated by applying the crop-specific or representative residue-to-product ratios described in the Materials and Methods section. Scenario-available residue quantities were subsequently calculated using the corresponding crop-specific or representative availability coefficients (Table 3).

For example, wheat residue generation was calculated as:

$$R_{wheat} = 31{,}000.5 \times 0.45 = 13{,}950.23\ t/year$$

Applying the 15% availability coefficient:

$$R_{(a,wheat)} = 13{,}950.23 \times 0.15 = 2{,}092.53\ t/year$$

The total gross crop-residue production was estimated at 24,508.70 t/year. After the application of crop-specific or representative availability coefficients, approximately 4,686.04 t/year was classified as scenario-available biomass for bioenergy production. Wheat generated the largest gross residue quantity, at 13,950.23 t/year, followed by other cereals and pulses at 8,081.37 t/year. Their scenario-available quantities were 2,092.53 t/year and 1,212.20 t/year, respectively. These values represent scenario-based technical residue availability rather than practically or economically recoverable biomass.

3.4. Theoretical Energy and Electricity-generation Potential

The potential for bioenergy production was calculated based on the amount of residues available for bioenergy production and the energy characteristics of each biomass type. The theoretical energy potential was estimated using the crop-specific or representative lower heating values presented in the Materials and Methods section. Unlike the

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previous uniform-energy-content approach, crop-specific LHV values were used in order to maintain consistency between feedstock characteristics and calculated energy potential (Table 4).

For wheat:

$$E_{(th,wheat)} = 2{,}092.53 \times 1000 \times 17.90$$

$$E_{(th,wheat)} = 37{,}456{,}354.13\ MJ/year$$

Equivalent to:

$$E_{(th,wheat)} = 10{,}404.54\ MWh/year$$

Applying the adopted electrical conversion efficiency of 25%:

Table 3: Gross and scenario-available crop-residue potential

Crop category	Production (t/year)	RPR	Gross residue (t/year)	Availability (%)	Scenario-available residue (t/year)
Wheat	31,000.5	0.45	13,950.23	15	2,092.53
Other cereals and pulses	8,506.7	0.95	8,081.37	15	1,212.20
Sugar beet	1,424.9	1.00	1,424.90	50	712.45
Sunflower	33.0	0.60	19.80	60	11.88
Potato	622.5	0.10	62.25	50	31.13
Vegetables	1,214.5	0.41	497.95	50	248.97
Melon crops	19.9	0.15	2.99	50	1.49
Fruits and berries	1,326.5	0.30	397.95	80	318.36
Grapes	237.6	0.30	71.28	80	57.02
Total	—	—	24,508.70	—	4,686.04

Table 4: Theoretical energy and electricity-generation potential

Crop category	Available residue (t/year)	LHV (MJ/kg)	Theoretical energy (MJ/year)	Theoretical energy (MWh/year)	Electricity potential at 25% (MWh/year)
Wheat	2,092.53	17.90	37,456,354.13	10,404.54	2,601.14
Other cereals and pulses	1,212.20	17.50	21,213,583.13	5,892.66	1,473.17
Sugar beet	712.45	17.21	12,261,264.50	3,405.91	851.48
Sunflower	11.88	14.20	168,696.00	46.86	11.72
Potato	31.13	15.34	477,457.50	132.63	33.16
Vegetables	248.97	15.29	3,806,789.53	1,057.44	264.36
Melon crops	1.49	20.50	30,596.25	8.50	2.12
Fruits and berries	318.36	18.05	5,746,398.00	1,596.22	399.06
Grapes	57.02	16.37	933,482.88	259.30	64.83
Total	4,686.04	—	82,094,621.91	22,804.06	5,701.02

The total theoretical energy potential of the scenario-available crop residues was approximately 82.09 million MJ/year, equivalent to 22,804.06 MWh/year or 22.80 GWh/year. After application of the adopted 25% electrical conversion efficiency, the estimated electricity-generation potential was approximately 5,701.02 MWh/year, or 5.70 GWh/year. Wheat was the largest individual contributor, providing approximately 2,601.14 MWh/year and accounting for approximately 45.6% of total electricity-generation potential. Other cereals and pulses contributed approximately 1,473.17 MWh/year, corresponding to approximately 25.8%. Together, wheat and other cereals and pulses accounted for approximately 71.5% of total estimated electricity-generation potential.

3.5. Potential Greenhouse Gas Emission Reduction

The potential reduction in greenhouse gas emissions was estimated assuming that electricity generated from agricultural residues replaces electricity supplied by the national power grid (Table 5).

In the revised assessment, a grid emission factor of 0.4066 t CO_2/MWh was applied instead of the previously adopted 0.48 t CO_2/MWh value.

Using the estimated electricity-generation potential of 5,701.02 MWh/year:

$$GHG_{red} = 5{,}701.02 \times 0.4066$$

$$GHG_{red} = 2{,}318.03\ t\ CO_2 - eq/year$$

or approximately:

$$GHG_{red} = 2.32\ kt\ CO_2 - eq/year$$

The estimated 2.32 kt CO_2-eq/year represents a gross grid-displacement scenario rather than a complete life-cycle greenhouse gas benefit. Emissions associated with harvesting, collection, transportation, storage, preprocessing, plant construction, facility operation, and auxiliary energy use were not included in the calculation.

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Table 5: Potential greenhouse gas emission reduction

Crop category	Electricity potential (MWh/year)	Grid emission factor (t CO_2/MWh)	Potential GHG reduction (t CO_2-eq/year)
Wheat	2,601.14	0.4066	1,057.62
Other cereals and pulses	1,473.17	0.4066	598.99
Sugar beet	851.48	0.4066	346.21
Sunflower	11.72	0.4066	4.76
Potato	33.16	0.4066	13.48
Vegetables	264.36	0.4066	107.49
Melon crops	2.12	0.4066	0.86
Fruits and berries	399.06	0.4066	162.26
Grapes	64.83	0.4066	26.36
Total	5,701.02	—	2,318.03

4. DISCUSSION

The results demonstrate that agricultural crop residues constitute a potentially useful renewable-energy resource in the East Zangezur Economic Region; however, the quantity considered available for bioenergy production is substantially lower than the gross amount generated. Gross crop-residue production was estimated at 24,508.70 t/year, whereas approximately 4,686.04 t/year was classified as scenario-available biomass. This distinction is important because treating all generated residues as available may substantially overestimate regional bioenergy potential. Agricultural residues perform important agronomic functions and may also have competing non-energy uses. Similar distinctions between theoretical residue generation and technically available biomass are emphasized in agricultural-residue assessments and international bioenergy frameworks (Fartash Naeimi et al., 2023; IRENA, 2023). Cereal residues represented the dominant component of the estimated resource. Wheat provided the largest individual electricity-generation potential, followed by other cereals and pulses. Together, these categories accounted for approximately 71.5% of total estimated electricity-generation potential. This reflects the agricultural structure of East Zangezur, where cereal production, particularly wheat, represents a major component of crop production. The predominance of cereal residues is consistent with broader assessments of agricultural biomass in Azerbaijan (Fartash Naeimi et al., 2023).

An important methodological consideration was the statistical treatment of wheat. In the official agricultural statistics, wheat is included within "cereals and pulses (total)". Treating wheat and the complete aggregated category as independent quantities would therefore result in double counting. After subtraction of wheat production, 8,506.7 t/year was attributed to other cereals and pulses. This correction ensured internal consistency throughout the residue, energy, electricity, and GHG calculations.

However, uncertainty remains within the aggregated "other cereals and pulses" category because it may contain crops with different RPRs, LHVs, and residue-availability characteristics. A barley-straw proxy was therefore used as a representative parameter. Similar uncertainty applies to vegetables and fruits-and-berries, for which tomato-pruning and apple-pruning proxies were used. Future assessments would benefit from crop-specific production statistics for the individual crops included within these aggregated categories. The use of crop-specific or representative availability coefficients provides a more realistic screening approach than applying one uniform residue-recovery fraction to every crop category. Crop residues differ in agronomic function, competing uses, harvesting characteristics, and recoverability. Residues retained in agricultural systems contribute to nutrient cycling, erosion protection, moisture conservation, and maintenance of soil organic carbon. IRENA (2023) similarly emphasizes that agricultural-residue mobilisation should account for sustainability constraints, competing uses, and local agronomic conditions. Accordingly, the coefficients used in this study should be interpreted as scenario parameters rather than direct measurements of sustainable residue removal in East Zangezur.

The importance of residue retention is supported by recent research on soil organic carbon. Alvarez (2024) reported that crop-residue harvesting can reduce soil organic-carbon stocks, indicating that intensive residue extraction may adversely affect long-term soil-carbon conservation. Díaz et al. (2024) similarly emphasized that agricultural biomass utilization should be balanced against maintenance of soil fertility and carbon stocks. Consequently, future bioenergy development in East Zangezur should not focus solely on maximizing residue extraction. The scenario-available biomass contained a theoretical energy potential of approximately 22.80 GWh/year. After applying the adopted electrical conversion efficiency of 25%, estimated electricity-generation potential decreased to approximately 5.70 GWh/year. This difference demonstrates why theoretical biomass energy and electricity-generation potential should be reported separately. The adopted 25% conversion efficiency represents a baseline scenario and should not be interpreted as the efficiency of every biomass-conversion technology. Actual performance depends on plant size, biomass moisture, feedstock characteristics, preprocessing, system configuration, and operating conditions (Morrone et al., 2022).

Spatial and logistical constraints are also important for the practical utilization of residues in East Zangezur. The

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region contains considerable variation in elevation and terrain, which may influence road accessibility, transport distance, harvesting operations, and transportation costs. IRENA (2023) identifies harvesting, collection, preprocessing, transport, storage, seasonal availability, and spatial feedstock dispersion as key limitations on agricultural-residue mobilization. Consequently, the estimated 4,686.04 t/year of scenario-available biomass should not be interpreted as the amount that could automatically be delivered to a future bioenergy facility. A GIS-based assessment integrating road networks, slope, residue density, transport distance, storage locations, and candidate plant sites would be required to determine practical recoverability.

The estimated electricity-generation potential of 5,701.02 MWh/year corresponds to a potential grid-displacement benefit of approximately 2,318.03 t CO_2-eq/year, or 2.32 kt CO_2-eq/year, based on the adopted grid emission factor of 0.4066 t CO_2/MWh. This value represents a gross displacement estimate rather than a complete life-cycle GHG benefit. Emissions associated with harvesting, collection, transportation, storage, preprocessing, plant construction, operation, and auxiliary energy consumption were not included. A complete life-cycle assessment would therefore be required to determine the net climate benefit of a specific future crop-residue bioenergy system. Overall, agricultural crop residues could make a modest but environmentally relevant contribution to renewable-energy development in East Zangezur. Their most appropriate application may involve decentralized or locally integrated energy systems in areas where sufficient biomass can be collected within economically reasonable distances. Future development should be supported by field-based residue measurements, GIS-based logistics analysis, sensitivity assessment, technology-specific techno-economic evaluation, and life-cycle assessment.

5. CONCLUSION

This study assessed the bioenergy potential of agricultural crop residues in the East Zangezur Economic Region using official 2024 agricultural production data and a deterministic, scenario-based methodological framework consistent with the FAO BEFS Rapid Appraisal approach. The total gross crop-residue generation was estimated at 24,508.70 t/year. After applying crop-specific or representative residue-availability coefficients, approximately 4,686.04 t/year was classified as scenario-available biomass for bioenergy production. The corresponding theoretical energy potential was approximately 22.80 GWh/year. Under the adopted electrical conversion efficiency of 25%, this resource could theoretically generate approximately 5.70 GWh/year of electricity. Wheat and other cereals and pulses represented the dominant contributors, together accounting for approximately 71.5% of the total estimated electricity-generation potential. Under the adopted grid-displacement scenario with an emission factor of 0.4066 t CO_2/MWh, the estimated electricity generation corresponds to a potential greenhouse gas reduction of approximately 2.32 kt CO_2-eq/year. The results demonstrate that agricultural crop residues could provide a modest but environmentally relevant contribution to renewable-energy development in East Zangezur. However, the estimated values represent scenario-based technical potential rather than practically or economically recoverable biomass. The assessment does not explicitly account for field-specific collection losses, competing residue uses, seasonal availability, transportation distance, storage, spatial distribution, plant siting, or technology-specific economic performance. Future studies should therefore combine field-based residue measurements with GIS-based logistics analysis, sensitivity assessment, techno-economic evaluation, and life-cycle assessment in order to determine the practically and economically recoverable bioenergy potential of agricultural residues in the region.

Declarations

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Data Availability: All the data is available in the article.

Ethics Statement: Not applicable.

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