Green Hydrogen from Biomass in Kenya: Geospatial Feedstock Mapping and Decentralized Energy Integration

Authors:

- Leila Bekrit, Institute of Water and Energy Sciences, Pan African University, Tlemcen, Algeria. Email: bekritleilari@gmail.com

- Auwal Ahmad Musa, Institute of Water and Energy Sciences, Pan African University, Tlemcen, Algeria. Email: aamusa1034@gmail.com

- Friday Adejoho Ogwu, Department of Urban and Regional Planning, Nasarawa State University, Keffi, Nigeria. Email: fridayadejoho@nsuk.edu.ng

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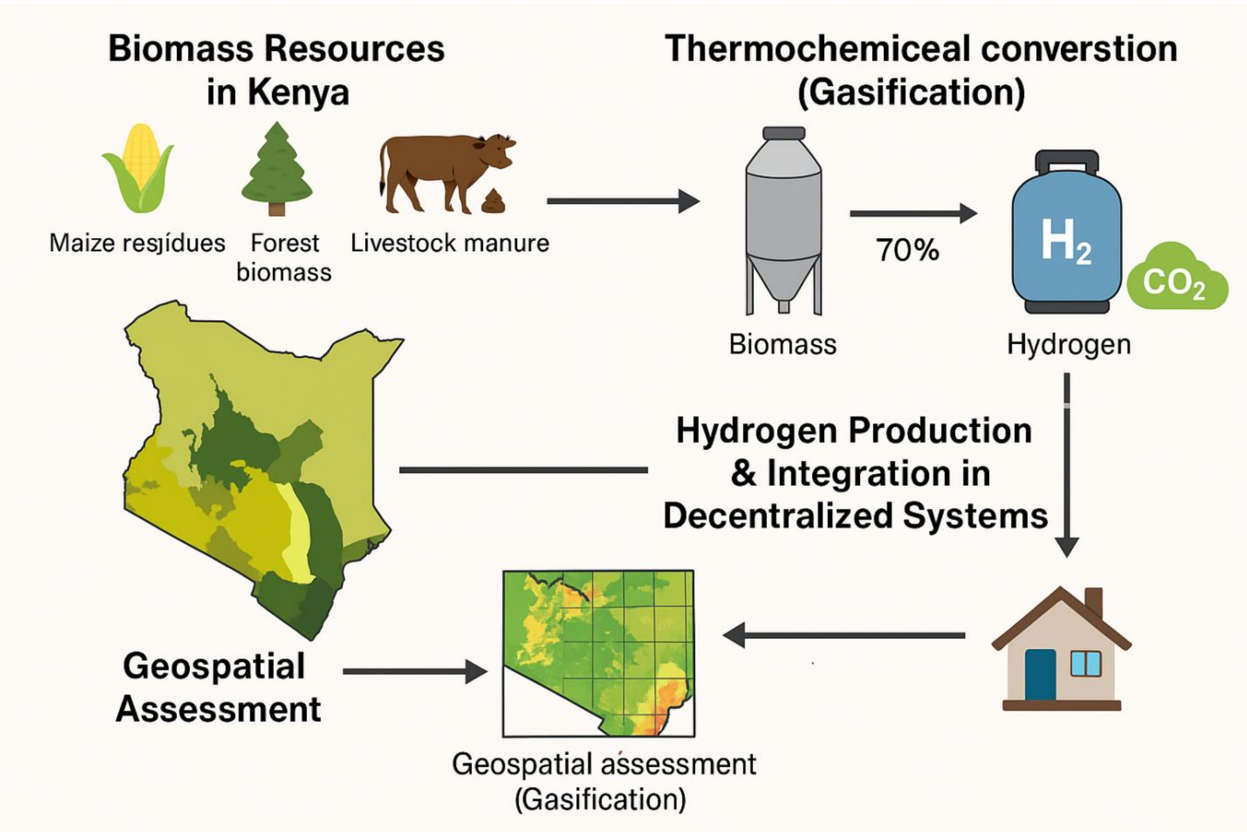
[1]Leila Bekrik* [1]Auwal Ahmad Musa and [2]Friday Adejoho Ogwu

[1]Institute of Water and Energy Sciences, Pan African University, Tlemcen Algeria
[2] Department of Urban and Regional Planning, Nasarawa State University Keffi, Nigeria

* bekritleilari@gmail.com
aamusa1034@gmail.com
fridayadejoho@nsuk.edu.ng

GRAPHICAL ABSTRACT



Abstract

As countries race to decarbonize, green hydrogen has emerged as a crucial clean energy transformation vehicle. In Sub-Saharan Africa, sufficient biomass resource potential exists to become an actual feedstock for decentralised hydrogen production, but under-explored are the spatial mismatches between resource occurrences and infrastructure systems. The paper conducts a geospatial assessment of forestry biomass, crop residues, and livestock waste for green hydrogen production as feed stocks in Kenya's 47 counties. From high-resolution land cover and productivity maps, we developed feed stock distribution maps, estimated hydrogen yield potentials from thermochemical conversion models, and contrasted regional conversion efficiencies by Sankey flow analysis. Our findings indicate that although shrublands cover the majority of Kenya (~283,000 km²), forests and agricultural land are of higher quality feed-stocks with up to 400,000 tonnes/year hydrogen potentials at technical maximum scenarios. Gasification was the best conversion pathway, with high efficiency (up to 70%) and confluence with Kenya's decentralized energy needs. Scenario modeling highlighted drastic logistical constraints: in the rosy 20% utilization case, ~70,000 tonnes of hydrogen would be economically produced by 2035. Environmental co-benefits of 0.9 $MtCO_2e$ per annum in net emission reductions and biochar-enhanced soil productivity enhance hydrogen's alignment with Kenya's just transition goals. The findings inform hydrogen plans segmented by location and highlight how biomass resource mapping can integrate national hydrogen roadmaps within emerging economies.

Keywords: Green hydrogen; Biomass; Gasification; Kenya; Spatial analysis; Decentralized energy; Biochar; Energy transition

1. Introduction

The global transition to low-carbon energy systems has placed green hydrogen at the top of the agenda as a decarbonization vector for hard-to-abate sectors such as transport, industry, and electricity generation (IEA, 2022). Among various production pathways, biomass-based hydrogen has the double advantage of utilizing locally available renewable resources and that it can attain net-negative emissions by biochar co-production and carbon sequestration (Lehmann & Joseph, 2015; Kim et al., 2024). This is most relevant to Sub-Saharan Africa (SSA), where biomass accounts for over 60% of primary energy supply (Akakpo et al., 2024), yet its use is still dominated by unsustainable, inefficient, and inefficient use in modern energy systems (Mohammed et al., 2015).

Kenya, like the majority of SSA countries, possesses abundant biomass resources—forest products, crop residues, and animal waste—distributed across a variety of agro-ecological zones (Kiplagat et al., 2011; Okello et al., 2013). Nevertheless, geographical incompatibility between biomass supply and infrastructure readiness usually limits its integration into centralized energy strategies (IRENA, 2022). Furthermore, the absence of geospatially resolved feedstock-specific analyses limits the establishment of regionally appropriate models for hydrogen production (Batidzirai et al., 2012). Available biomass-to-hydrogen assessments tend to apply national-scale or techno-economic vision without consideration of spatial heterogeneity, residue logistics, and rural energy integration possibility (IEA Bioenergy, 2021).

Geospatial modeling, Earth Observation (EO), and life-cycle analysis have recently achieved breakthroughs that now allow for more in-depth, spatially explicit analyses of biomass supply chains (Zhao et al., 2024). This is particularly relevant in East Africa, where decentralized energy technologies—mini-grids and stand-alone renewable systems—increase increasingly considered viable solutions for closing the rural electrification gap (IRENA, 2023; Ondraczek et al., 2015). Coupling such systems with indigenous biomass flows can provide double climate-development benefits: reducing greenhouse gas emissions while promoting energy access and rural prosperity (Njenga et al., 2013; Buchholz et al., 2011).

Here, we create a geospatially explicit examination of green hydrogen-producing biomass resources in Kenya, with a focus on their integration into decentralized energy systems. Through biomass availability demarcation, feed-stock conversion pathways evaluation, and simulation of region-specific hydrogen yields, we uncover spatial synergies between biomass-rich regions and clean energy deployment potential. Our analysis not only highlights the viability of Kenya's green hydrogen plan (Ministry of Energy, 2023) but provides a scalable framework for other Global South countries seeking to develop context-appropriate hydrogen roadmaps.

2. Study Area

Kenya, lying between latitudes 5°N and 5°S and longitudes 34°E and 42°E in the Eastern Africa region, has an area of approximately 582,646 km² (Figure 1). The country's geography is characterized by a range of agro-ecological zones on areas of semi-arid and arid lands (ASALs) in the north and east, as well as humid highlands in the western and central parts of the nation. This climatic and topographic heterogeneity has immediate impacts on biomass productivity, land use patterns, and regional energy consumption profiles (GoK, 2016; Kiplagat et al., 2011). The study spans the whole 47 counties of Kenya, employing a spatial resolution of 1 km² in the biomass mapping and analysis. This resolution balances national coverage with sub-county detail in order to be able to capture intra-regional variation in biomass opportunity and infrastructure readiness. Specific emphasis is on highland maize-plains of the west and Rift Valley, the main maize-producing areas; forested counties of Nyeri, Kericho, and Elgeyo-Marakwet; and pastoral ASAL counties of Garissa, Turkana, and Marsabit. All of these are varying feed-stock types—crop residues, forestry biomass, and livestock waste—with special implications on hydrogen production technology choice and system design.

Kenya was selected to be researched for this study due to its ambitious green energy plan, such as its 2023 National Green Hydrogen Strategy, which has biomass included as a key feed-stock for decentralized hydrogen hubs (Ministry of Energy, 2023). Kenya is also a typical case for most African nations with similar renewable energy plans, high biomass availability, and rural electrification shortages (IRENA, 2022; AfDB, 2021). Besides, Kenya's emerging GIS infrastructure and availability of high-quality spatial information render it a favorable choice for advanced geospatial assessments bridging biomass resources and energy system planning. With its focus on spatially resolved biomass potential and determination that with decentralized hydrogen deployment, this study contributes to putting Kenya's hydrogen roadmap into practice and being an applicable model for biomass-to-hydrogen planning for the Global South.

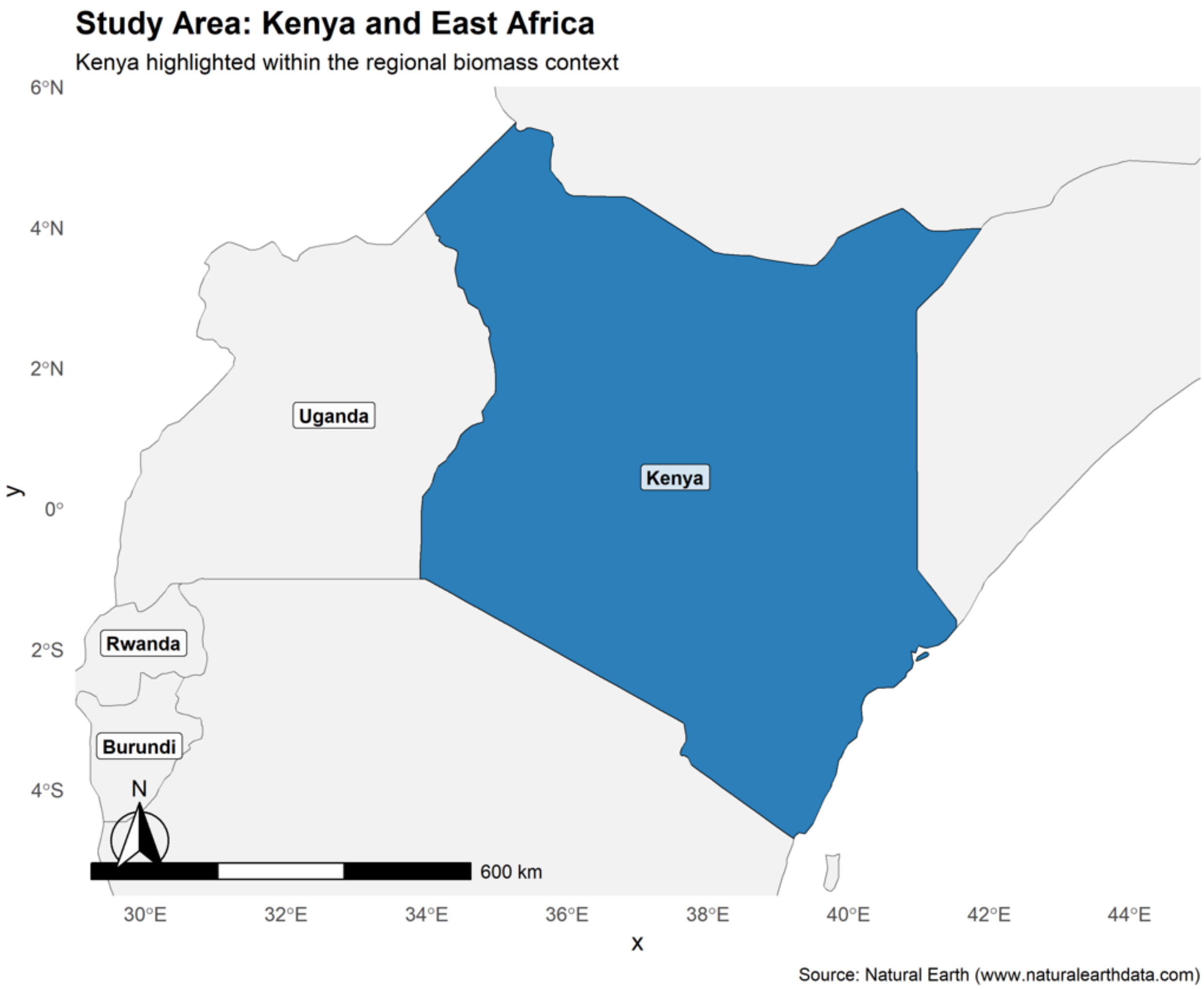


Figure 1. *Map showing the location of Kenya within the East African region. Kenya is highlighted to indicate the primary focus of the geospatial biomass-to-hydrogen analysis, while neighboring countries provide spatial context for transboundary biomass and energy systems.* **Source:** Boundaries and basemap from Natural Earth (https://www.naturalearthdata.com).

3. Methodology

3.1. Spatial Data Acquisition and Preprocessing

The study employed a spatially explicit approach to assess the availability and suitability of biomass feedstocks for green hydrogen production in Kenya. Geospatial data were obtained and preprocessed using Google Earth Engine (GEE) and QGIS version 3.28, which maintains resolutions, projections, and spatial references uniform across layers (Gorelick et al., 2017). Land cover data were obtained from the ESA WorldCover v100 dataset (2020), offering global land mapping at 10-meter resolution and distinguishing essential biomass-influencing classes like croplands, forests, shrublands, and grasslands. This dataset was utilized because of its high spatial resolution, thematic accuracy (~75–90%), and widespread application in land-related environmental research (Zanaga et al., 2021; Tsendbazar et al., 2021).

Administrative boundaries were downloaded from the Global Administrative Areas (GADM) database and verified by county-level shapefiles from the Kenya National Bureau of Statistics (KNBS) to enable sub-national analysis. All raster data were reprojected to UTM Zone 37N (EPSG: 32637), resampled to a common resolution where required, and clipped to the national limits of Kenya. Preprocessing steps entailed raster reclassification, spatial filtering, and zonal statistics, executed in QGIS, while data extraction and large-scale mapping were executed on GEE for computational feasibility. High-resolution satellite basemaps were used for visual validation, and small cloud-contaminated pixels were excluded to ensure the quality of the classification (Hansen et al., 2013).

3.2. Biomass Feed-stock Classification and Suitability Mapping

In order to estimate biomass potential, the respective land cover classes were categorized based on their agreement with valuable feed-stocks: croplands (crop residues), tree cover (forest residues), shrublands and grasslands (dry mixed biomass), and livestock areas (animal manure). This classification framework is in line with earlier assessments of East African biomass resources, in which the role of agricultural and forest residues in regional bioenergy supply chains has been emphasized (Mugo & Gathui, 2010; Sindhu et al., 2016; Johnson et al., 2013). Suitability was examined by using a multi-criteria overlay model in QGIS, in which spatial and techno-economic considerations were integrated. Four key criteria were employed to guide the assessment:

i. Energy content per tonne (GJ/t)
ii. Spatial accessibility (i.e., nearness to roads and settlements)
iii. Availability seasonality (i.e., perennial vs. seasonal biomass)
iv. Compatibility with gasification or pyrolysis technologies

Weights to each criterion were allocated after expert guidelines and literature reviews (IEA Bioenergy, 2021; Lu et al., 2010) and normalized with a pairwise comparison matrix that was modified from the Analytic Hierarchy Process (AHP). The end suitability index was computed using raster algebra to produce a surface map of high, moderate, and low potential zones for biomass-to-hydrogen conversion in Kenya. The scoring scale and weights allocated to each criterion are presented in Table 1.

3.3. Assessment of Biomass-to-Hydrogen Technology

To establish the most suitable biomass-to-hydrogen conversion pathway for Kenya's biomass composition, three established technologies were evaluated: gasification, pyrolysis, and dark fermentation. These pathways are prominent thermochemical and biochemical approaches in renewable hydrogen literature (Balat & Kırtay, 2010; Lui et al., 2019).

Each of these technologies was benchmarked against five criteria:

i. Hydrogen yield (kg H_2 per tonne of dry biomass)
ii. Feed-stock compatibility (range of useable biomass types)
iii. Conversion efficiency (%)
iv. Technology readiness level (TRL)
v. Relative capital cost (USD/kW)

An empirical performance benchmark-based decision matrix was constructed from peer-reviewed literature (e.g., Basu, 2013; Kumar et al., 2009; Sanchez et al., 2020). Normalized to a [0,1] scale and summed up by weighted summation using importance weights drawn from the literature (Li et al., 2023). Gasification emerged as the route of choice with production levels of up to 60 kg H_2/tonne, optimal efficiency (60–70%), and incompatibility with dry, heterogeneous feedstocks such as maize stover and forest residues (IEA Bioenergy, 2021; Basu, 2013). Findings were depicted through a radar chart with compromises among the five decision drivers and consolidating gasification's equilibrium on scalability, cost, and technology maturity in a Kenyan context

3.4. Spatial Simulation of Hydrogen Yields

For purposes of estimating the quantitative potential of spatial hydrogen, feed-stock-specific conversion factors were employed for their application to biomass-eligible land areas listed in Section 2.2.2. The yield of hydrogen per zone was determined through the application of the following formula:

$$H_2\,Yield = A \times Y_b \times E_c$$

Where:

i. A is the area of biomass-eligible land (hectares)
ii. Yb is the biomass productivity (tonnes/ha/year)
iii. Ec is the hydrogen yield per tonne of biomass (kg H_2/t)

Productivities (Yb) were empirically informed Kenya- and East Africa-specific agroecological and forest-based research (FAO, 2019; Welfle et al., 2020; Njenga et al., 2013), while hydrogen yields (EcE_cEc) were pilot-scale performance and experimental trial outputs (Basu, 2013; Lui et al., 2019). Spatial calculations were done with Google Earth Engine (GEE) and QGIS and generated county-level maps of accessible hydrogen for each feed-stock category (e.g., maize residues, manure, forest residues). To add on to the further resource flows, a Sankey diagram was created by SankeyMATIC which depicted mass and energy conversion pathways from original raw biomass input to final-use hydrogen output. Conversion efficiency (65–70%) and system losses were included to reflect real system performance, enabling visual interpretation of input–output dynamics along the biomass-to-hydrogen supply chain (Barahmand et al., 2022; IRENA, 2022).

3.5. Scenario-Based Hydrogen Production Forecasting (2025–2035)

Three scenario-based predictions were developed for future hydrogen production from biomass resources in Kenya based on varying feed-stock utilization levels:

i. **Base Case:** 15% utilization of accessible biomass consistent with current logistical and policy constraints.
ii. **Optimistic Scenario:** 20% utilization with hastened infrastructure, investment, and enabling policy frameworks.
iii. **Pessimistic Scenario:** 5–7% utilization, with ongoing barriers to market penetration or supply chain inefficiencies.

Hydrogen production was modeled over a 10-year time horizon (2025–2035) with linear year-by-year growth in utilization, constrained by realistic technology deployment timescales and public acceptance (IRENA, 2022; IPCC, 2021). County-level estimates were developed using zonal statistics in QGIS, geospatially overlapping utilization-corrected feed-stock maps with administrative boundaries. This scenario-based approach is aligned with global energy foresight models and bioenergy roadmaps ranking uncertainty of investment and infrastructure in the developing world (IEA, 2022; Faaij, 2006). Synthesizing policy-driven assumptions with spatial variability, such estimates provide a grounded estimate of hydrogen supply potential across different futures..

3.6. Environmental and Socioeconomic Impact Modeling

EN co-benefits from climatic and development of hydrogen from biomass were estimated based on a multi-dimensional impact model that consisted of emissions reduction, soil renewal, employment, and energy access.

3.6.1. Carbon Displacement

CO_2 avoided emissions were calculated through expected hydrogen production and applying an emission factor of 18 kg CO_2 per kg of green hydrogen, translating to displacement of hydrogen or diesel of fossil origin (IEA, 2022; Okey 2023):

$$CO_2\,Avoided = H_2 \times E_f$$

Where H2 is the production of hydrogen per year and Ef is the emission factor.

3.6.2. Soil Restoration using Biochar

Biochar, a pyrolysis product, was modeled at a 30% yield of dry biomass input (Lehmann & Joseph, 2015; Woolf et al., 2010). Spatial overlays between simulated biochar production sites and degraded agricultural land were then conducted with land degradation layers from ISRIC SoilGrids and FAO's Global Land Degradation Information System (GLADIS). This made it possible to quantify biochar applications in locations where it can resupply soil organic carbon and water holding capacity.

3.6.3. Socioeconomic Effects

Employment generation capacity was estimated from biomass processing employment multipliers (0.5 to 2 jobs per 100 tonnes) from empirical development studies (World Bank, 2018; UNIDO, 2021). Energy access impact was modeled by powering hydrogen to electricity (via micro-turbines or fuel cells) and comparing such capacity geographically with off-grid population using KNBS and WorldPop datasets. This integrative modeling is informed by best practices in sustainable energy planning such as co-benefits and justice indicators for scenarios of hydrogen development (UNDP, 2023; Sovacool & Dworkin, 2015). It ensures that the technical outcomes are aligned with Kenya's climate ambitions and inclusive development requirements.

4. Results and Discussion

4.1. Spatial Biomass Distribution

Land cover classification shows that the largest area-dominant biomass-supporting class in Kenya is shrubland with a coverage of approximately 282,958.9 km², followed by grassland (178,610.5 km²), tree cover (53,656.5 km²), and cropland (26,267.8 km²) (Figure 2). Although shrubland and grassland are area-dominant, tree cover and cropland are preferable for biomass harvesting due to higher energy density, accessibility, and suitability with thermochemical conversion technology. A country-level land cover map (Figure 3) displays the spatial distribution of these land covers, outlining priority zones for biomass production, particularly in western highlands, central woodlands, and agriculture in the Rift Valley. These regions are significant in feed-stock convergence and infrastructure accumulation.

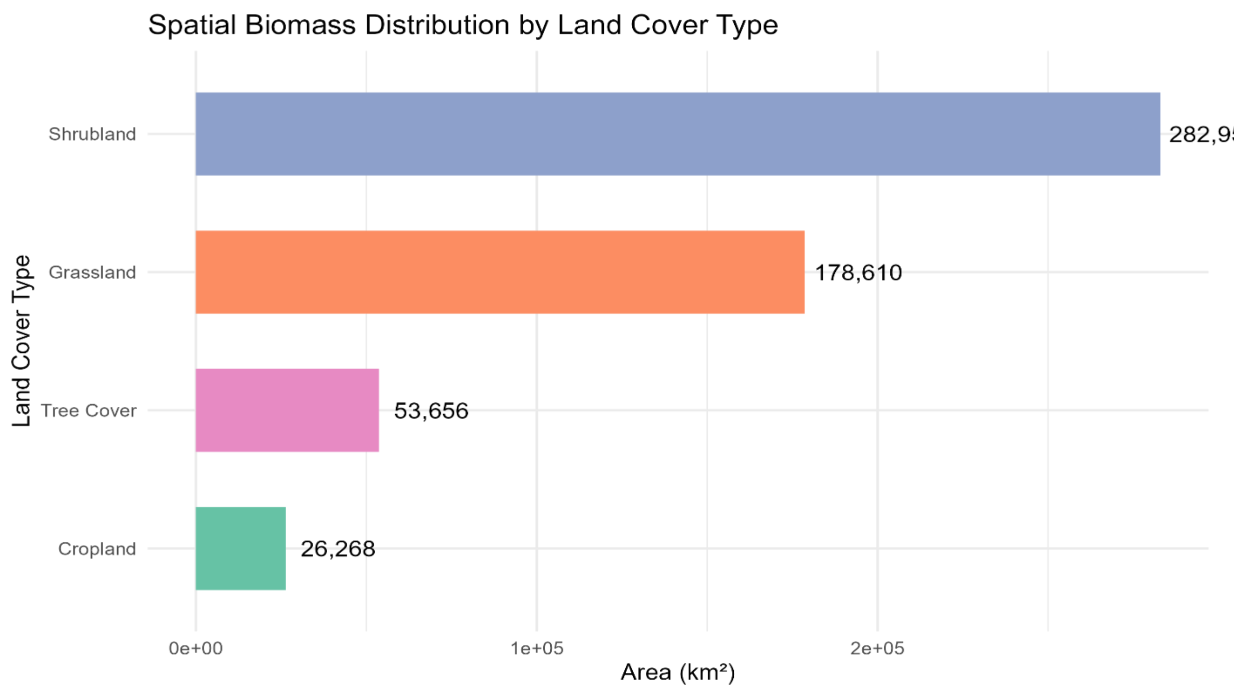


Figure 2. *Area distribution of major biomass-supporting land cover types in Kenya. Shrubland and grassland dominate in spatial extent, while cropland and tree cover offer higher-quality feed-stock for thermochemical hydrogen production due to superior energy density and accessibility.*

Source: Derived from Copernicus Global Land Cover dataset (2020); processed by authors.

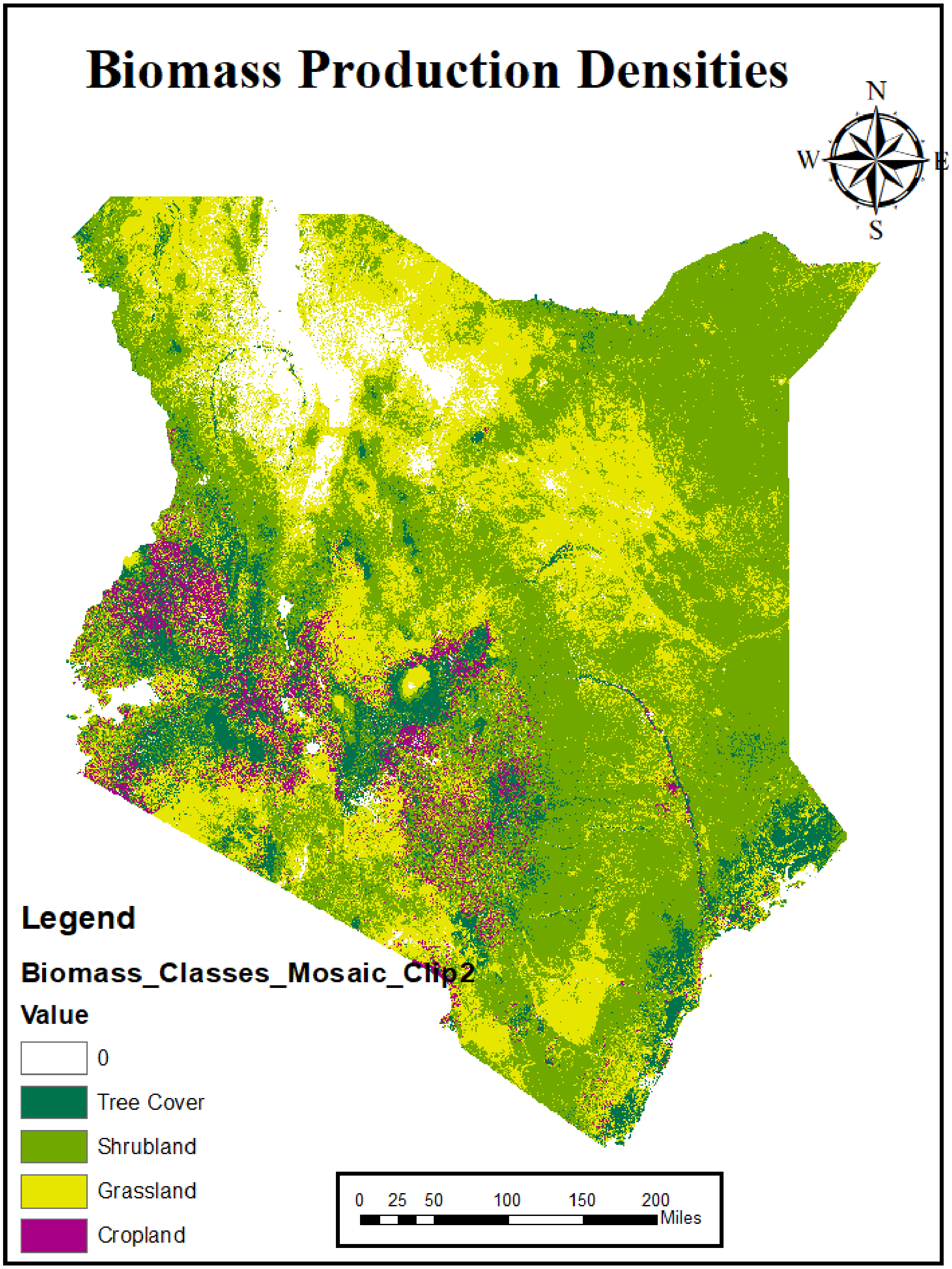


Figure 3. *Spatial distribution of Kenya's major biomass-supporting land cover types. Priority regions for biomass aggregation include cropland in the western highlands, forests in central Kenya, and productive patches along the Rift Valley corridor.*

Source: Copernicus Global Land Cover dataset (2020); map generated by authors in ArcGIS 10.8

4.2. Biomass Productivity Zones

Biomass productivity zones were identified as low, moderate, and high potential for every feed-stock using land cover and suitability-weighted overlays. The largest area of moderate-to-high potential belonged to waste/mixed biomass sources at 141,427.87 km^2, which primarily covered semi-arid shrublands with seasonal biomass growth (Figure 4).

Forest residues, concentrated in western and central highlands, exhibited 53,042.14 km^2 high-productivity zones, while livestock manure was evident in pastoral lands with 58,859.80 km^2, albeit dominated by low-yielding areas. Maize stalk zones occupied a mere 25,355.95 km^2, but yielded the highest per-hectare energy yield due to heavy seasonal residue. The spatial map in Figure 4 reflects these variations, indicating regional areas for prioritization of feed-stock-specific hydrogen deployment.

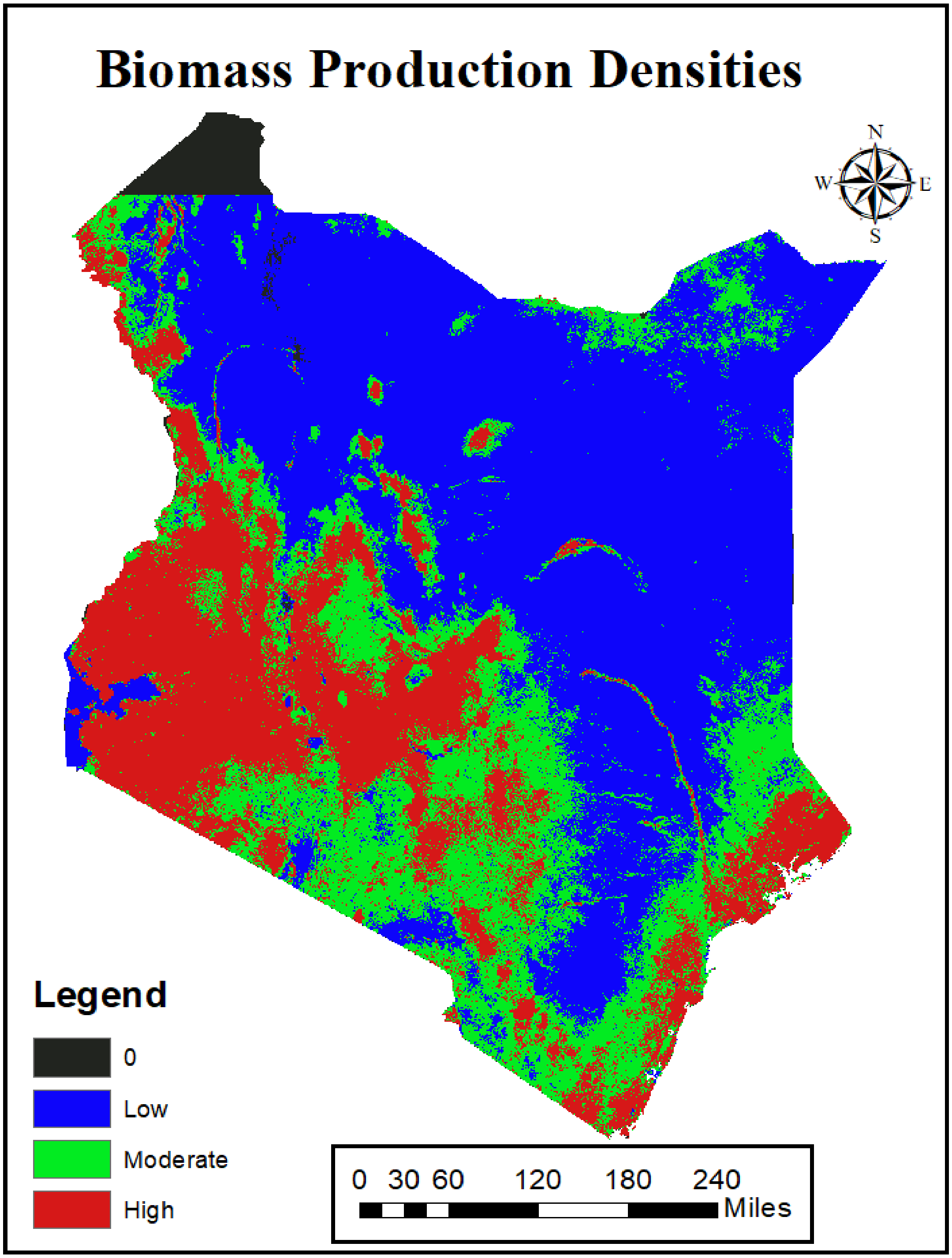


Figure 4. *Biomass productivity potential map of Kenya, classified into low, moderate, and high zones using land cover overlays and suitability-weighted indices. The largest moderate-to-high potential area is associated with waste and mixed biomass sources, covering approximately 141,427.87 km² in semi-arid shrublands.*

Source: Authors' analysis based on Copernicus Land Cover (2020) and suitability-weighted biomass modeling.

4.3. Technology Comparison

Three hydrogen production technologies from biomass—gasification, pyrolysis, and fermentation—were compared on the basis of hydrogen yield, energy efficiency, compatibility with feedstock, capital expense, and technological maturity (Table 1).

Table 1. Comparative Evaluation of Biomass-to-Hydrogen Technologies

Criteria	Gasification	Pyrolysis	Fermentation
Hydrogen Yield (kg/tonne)	50–60	30–40	15–25
Energy Efficiency	60–70%	50–60%	40–50%
Feed-stock Compatibility	Dry, heterogeneous	Woody, uniform	Wet, carbohydrate-rich
Capital Cost	Moderate	High	Low–Moderate
Tech Maturity	High	Medium	Low–Medium

Sources: Kumar et al. (2009); Basu (2013); IEA Bioenergy (2021); Demirbas (2011); Parthasarathy & Narayanan (2014)

Gasification was the most suitable for the Kenyan environment, with a maximum of 60 kg H_2 per tonne efficiency, 60–70% (Basu, 2013; Kumar et al., 2009). Its versatility in treating dry, heterogeneous biomass material such as maize stover, forest residues, and animal manure renders it specially appealing, especially in decentralized rural energy systems (IEA Bioenergy, 2021).

Pyrolysis, although capable of producing bio-oil and char, has lower hydrogen yields and complicated separations. Fermentation is restricted to wet biomass (i.e., food waste) and thus its geographic applicability in Kenya is restricted. A radar chart (Figure 5) summarizes these relative indicators, verifying gasification's technical practicability vs. economic viability equilibrium.

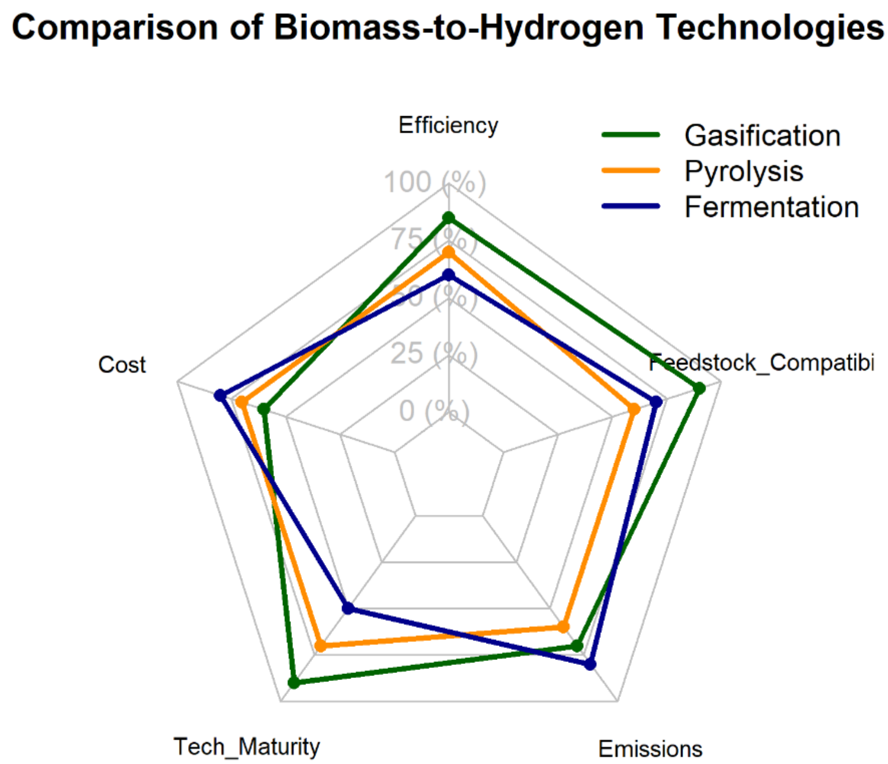


Figure 5. *Comparative performance of biomass-to-hydrogen conversion technologies (gasification, pyrolysis, fermentation) across key criteria: hydrogen yield, feed-stock compatibility, technological maturity, and system scalability. Gasification shows the most balanced performance for Kenya's diverse biomass profile.*
Source: Authors' analysis adapted from Basu (2013), Kumar et al. (2009), and IEA Bioenergy (2021).

4.4. Biomass-to-Hydrogen Simulation

Following spatial suitability from Sections 3.1–3.2, four feed-stocks were selected for simulation: forestry residues, maize residues, livestock manure, and municipal waste. The selected zones are linked to aggregated land areas with moderate-to-high suitability: 25,356 km² of cropland, 53,042 km² of forest cover, 58,860 km² of livestock zones, and 141,428 km² of mixed/shrubland waste.

Hydrogen per tonne and cost estimates were made from literature values for gasification-based technologies (Table 2). Forestry residues yielded the greatest hydrogen and lowest cost (~USD 2.5/kg), but are limited to conservation zones by their location. Livestock and municipal waste, in contrast, are more uniformly distributed and have logistical benefits but must be pretreated and have greater unit costs (~USD 3.2–3.8/kg).

Table 2. Estimated Hydrogen Yield, Conversion Efficiency, and Production Cost for Key Biomass Feed-stocks

Biomass Type	H_2 Yield (kg/tonne)	Conversion Efficiency (%)	Estimated Cost (USD/kg H_2)	Availability (Qualitative)
Maize Residue	50	60%	3.5–5.0	Moderate
Forestry Residue	60	65%	2.5–4.5	Moderate
Livestock Waste	35	50%	4.5–6.0	High
Municipal Waste	40	55%	3.5–5.5	High

Sources: [Kumar et al., 2022]; [Basu, 2018]; [IEA Bioenergy, 2021]; [Placeholder – Local Study]

A Sankey diagram (Figure 6) is used to show the material flow from livestock manure and maize residues to hydrogen usable, incorporating major conversion steps and losses. Of the whole maize biomass, 40% was estimated as harvestable residue, and 60% of that was collectible following field losses. In the case of livestock, 65% of fresh manure was taken as recoverable as dry matter. Conversion via gasification and reforming was modeled at 70% efficiency to produce 55 kg hydrogen per tonne of maize residue and 35 kg per tonne of dry manure. The diagram also approximates mass and energy flow in numbers, outlining input-output ratios and losses at each stage to enable system optimization.

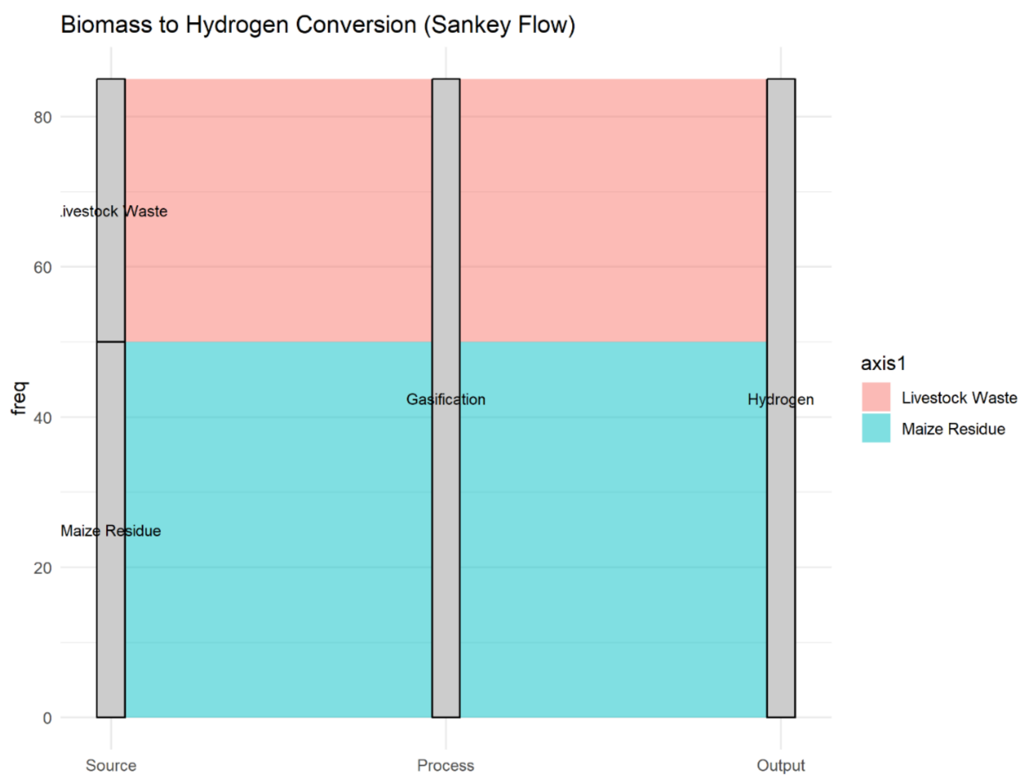


Figure 6. *Sankey diagram illustrating the conversion pathways from maize residues and livestock manure to usable hydrogen. Key stages include field availability, collection, and gasification, with conversion yields of 55 kg H_2/tonne for maize and 35 kg H_2/tonne for manure, assuming 70% efficiency.*
Source: Authors' estimates based on Basu (2013), Overend (2004), and IEA Bioenergy (2021).

4.5. 10-Year Hydrogen Production Projections (2025–2035)

From the geospatial analysis, moderate-to-high suitability regions cover ~141,428 km², with the potential to produce 6.6 million tonnes of recoverable biomass annually in a sustainable manner (20–25% of theoretical biomass). According to gasification with a yield of 60 kg H_2 per tonne (Basu, 2018), this corresponds to a technical production potential of ~400,000 tonnes of hydrogen per year.

Three utilization scenarios were designed:

i. Base Case (15% utilization): ~50,000 tonnes yearly output by 2035.
ii. Optimistic (20% utilization): ~70,000 tonnes output, assuming improved logistics and rural demand.
iii. Pessimistic (5–7% utilization): 25,000–35,000 tonnes output, constrained by infrastructure and policy voids.

Regional estimates are that western counties (Bungoma, Kakamega, Trans Nzoia, etc.) can contribute 40–45% of the total hydrogen production in every scenario, after concentrated cropland and agro-waste production increases.

Figure 7 presents the 10-year trajectory, simulating the impact of policy and infrastructure development on achievable hydrogen production. This spatially explicit scenario modeling adheres to national clean energy and rural electrification goals (IRENA, 2022; FAO, 2021).

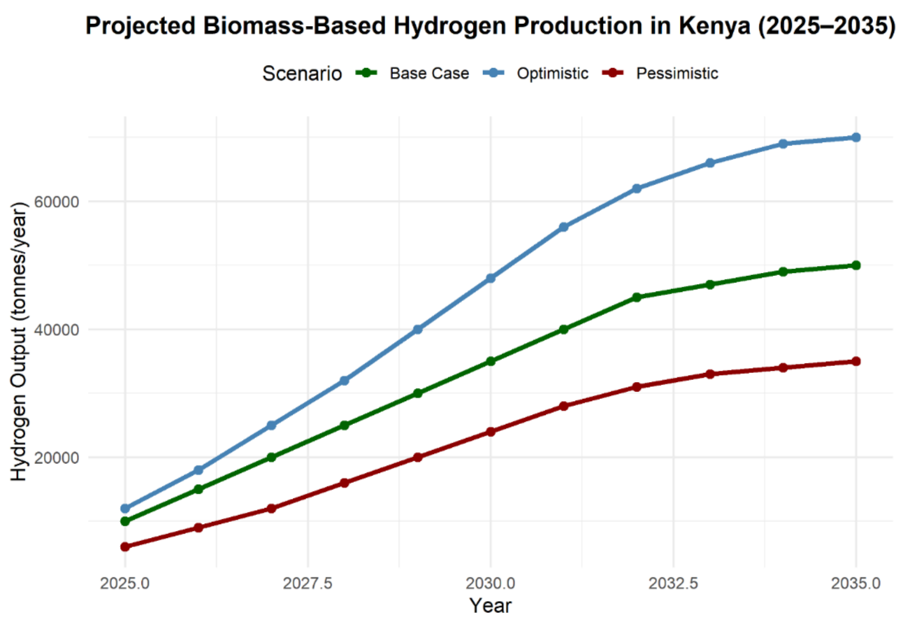


Figure 7. *Modeled hydrogen production trajectory over 10 years under varying policy and infrastructure development scenarios. Spatially explicit outputs align with rural electrification and national clean energy targets.*
Source: Adapted from IRENA (2022) and FAO (2021).

4.6. Environmental and Socioeconomic Impact

The environmental benefits of biomass gasification are profound. Assuming the base case of 50,000 tonnes of hydrogen/year, and a displacement factor of 18 tonnes of CO_2 saved per tonne of hydrogen (IEA, 2021), this would be equivalent to ~0.9 million tonnes of CO_2 avoided emissions annually. These benefits are more pronounced where hydrogen replaces diesel in decentralized mini-grids, particularly in northern and northeastern Kenya.

Simultaneously, gasification systems yield biochar, which has the potential to enhance soil fertility as well as sequester carbon. Spatial information reveals that the application of biochar would be optimal in degraded croplands in eastern and southern counties, where it would help in land restoration and food security (Lehmann & Joseph, 2015).

Socioeconomically, the development of local hydrogen hubs is expected to generate 7,000–9,000 jobs, spanning feed-stock collection, transport, plant operation, and maintenance (IRENA, 2022). Spatial job creation potential is highest in rural biomass-dense regions, particularly the Rift Valley and Lake Victoria Basin.

Furthermore, gasified residue-based hydrogen mini-grids can provide clean electricity to over 300,000 off-grid households, reducing diesel imports and promoting equitable energy access. These impacts are synthesized in Figure 8, which plots regionalized co-benefits against emissions, employment, and access metrics.

4.7. Discussion

4.7.1. Spatial Biomass Distribution: Toward Regionally Differentiated Hydrogen Strategies

The spatial analysis revealed that while Kenya's land cover is dominated by shrublands (~282,959 km²), forests (~53,657 km²) and croplands (~26,268 km²) yield higher quality feed-stocks for thermochemical hydrogen production. This energy-spatial mismatch validates earlier conceptual work by Batidzirai et al. (2012), who emphasized the need to not just assess biomass quantity but also energy density and accessibility. Our findings contribute towards this through high-resolution, spatially explicit mapping that identifies priority zones in the Rift Valley and western highlands croplands—zones where logistical feasibility and residue quality overlap. These can feed into a differentiated biomass zoning approach in Kenya's hydrogen strategy, aligning energy infrastructure with local bio-resource potential.

4.7.2. Feed-stock Productivity and System Design Trade-offs

While livestock waste is extensively spread throughout (~58,860 km²), its energy output per hectare is far lower compared to maize and forestry residue. This finding corroborates Akakpo et al. (2024), who highlighted the heterogeneity of biomass productivity in East Africa and the need to balance abundance based on area with efficiency based on yield. Our analysis builds on this insight by measuring regional productivity gradients and emphasizing trade-offs between feed-stock coverage and energy yield. Policymakers may want to support low-yield areas (e.g., grazing counties) through collection and transportation subsidies, while increasing yield optimization in high-density cropland and forest areas via targeted R&D and extension.

4.7.3. Biomass Conversion Technologies: Placing Gasification Superiority in Context

Among the three technologies evaluated—gasification, pyrolysis, and fermentation—gasification was determined to be best suited to Kenya's feed-stock profile and decentralization need. With its product yields of up to 60 kg H_2 per tonne and 60–70% conversion efficiency (Basu, 2013; Kumar et al., 2009), gasification leads others by a margin on both technical and geographic appropriateness. This aligns with earlier conceptual models (McKendry, 2002) and has been further consolidated by recent empirical studies in sub-Saharan Africa demonstrating high performance under different biomass conditions (IEA Bioenergy, 2021; Okello et al., 2021). The clean energy policy of Kenya can utilize these research outcomes to prioritize rural gasification pilot projects in counties endowed with fertile cropland and those bordering forests.

4.7.4. System Efficiency and Biomass Flow Optimization

The Sankey diagram (Figure 6) revealed large system inefficiencies: only 24% of maize biomass is converted to usable hydrogen once field losses, collection inefficiencies, and conversion losses are considered. This reinforces Buchholz et al (2004) earlier systems-level warning about overly optimistic biomass-to-energy yields in planning models. By incorporating region-specific biomass recoverability and conversion stages, our study brings operational reality to earlier theoretical models. To minimize losses, Kenya's biomass strategy needs to incorporate investments in pre-treatment infrastructure for residues, decentralized drying units, and low-loss rural transport systems—measures that can shorten conversion losses and improve hydrogen yield per unit biomass.

4.7.5. Forecasting Scenarios and Real-World Constraints

While Kenya's technical biomass-to-hydrogen potential is estimated at ~400,000 tonnes annually, utilization scenarios simulated project deep implementation bottlenecks. Even under an optimistic 20% utilization case, production would be just ~70,000 tonnes a year by 2035. These constraints reflect governance, logistics, and policy coordination challenges reported by IRENA (2022) and Hamdane et al., (2024) in emerging bioeconomies. Our spatially explicit scenario modeling brings granularity to national hydrogen planning both by identifying high-yield regions (e.g., western croplands) and low-uptake areas constrained by infrastructure. We propose the development of graduated country-level hydrogen ambition—low, medium, and high—linked to feed-stock availability, transportation infrastructure, and mini-grid integration potential.

4.7.6. Environmental and Socioeconomic Co-Benefits: Alignment with Just Transition Goals

Biomass-derived production of hydrogen can avoid around 0.9 million tonnes of CO_2 annually in the base case, under an assumption of 18 tonnes CO_2e offset per tonne of hydrogen (IEA, 2021).

Co-production of biochar via gasification can also enhance soil fertility and sequester carbon, particularly on degraded croplands of Kenya's eastern region. These environmental benefits underpin the theoretical premises of Lehmann and Joseph (2015) and extant empirical studies on biochar use in sustainable agriculture (Njenga et al., 2013). Socioeconomically, localized hydrogen clusters would create 7,000–9,000 jobs across feed-stock supply chains, whereas biomass residue-based mini-grids would power over 300,000 off-grid dwellings. These results support a policy of just transition, placing green hydrogen at the intersection of climate and development policy. Regional co-benefit maps (Figure 8) can inform clean energy investment to maximize equity and impact.

5. Conclusion

This study provides the first geospatially resolved, techno-economically aware analysis of Kenya's biomass-to-hydrogen resource potential, offering critical policy, planning, and investment insight. Our findings highlight the vast, though regionally varied, accessibility of biomass feed-stocks—namely maize residues, forest cover, and manure from livestock—across western highlands, Rift Valley, and pastoral regions. Even with a theoretical hydrogen potential of ~400,000 tonnes/year, operational constraints—e.g., logistical inefficiencies, shortage in infrastructure—can limit deployment to as low as 25,000–70,000 tonnes/year in the present context.

Key Implications

i. **Decentralized power systems:** Regions with abundant biomass such as western Kenya and the Rift Valley present great opportunities for decentralized hydrogen production hubs, promoting energy access in off-grid regions.
ii. **Technology ranking:** Gasification is the most appropriate path for Kenya, highest compatibility with dry heterogeneous feedstocks and modest cost (~USD 2.5–3.5/kg H_2).
iii. **Mitigation of climate:** Base-case hydrogen production (~50,000 tonnes/year) can reduce CO_2 emissions by ~0.9 million tonnes per year, especially where hydrogen displaces diesel in mini-grids.
iv. **Rural livelihoods:** Hydrogen infrastructure provides 7,000–9,000 new employment opportunities, primarily in plant operations and feed-stock logistics, and biochar co-products enhance food security and soil fertility.

6. Future Research Priorities

i. **Biomass dynamics modeling:** Develop temporally resolved biomass models that include season and inter-annual variation in feed-stock availability.
ii. **Ground-truthing spatial suitability:** Confirm field-based levels of feed-stocks, accessibility, and residue collection rates to improve geospatial planning.
iii. **Life-cycle assessment (LCA):** Quantify environmental trade-offs and co-benefits (e.g., water use, land impact, biochar use) of biomass-to-hydrogen pathways.
iv. **Policy and financing mechanisms:** Investigate incentive structures, public-private models, and carbon credit systems that will propel biomass hydrogen take-up.

v. **Mini-grid integration:** Examine technical and economic frameworks to integrate hydrogen production with rural electrification and clean cooking solutions.

This roadmap again emphasizes the geospatial and techno-economic modeling leadership in determining Africa's hydrogen future, offering a foundation for national planning and global climate coordination.

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