



**Politecnico
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Department of Environment, Land, and Infrastructure Engineering (DIATI)

Master of Science in Environmental and Land Engineering

Global Quantification of Sustainable Biomass Residues for CDR:

A Country-Level Assessment for Biochar-Based CDR in 2050

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Academic Year: 2025-2026

July 2026

Abstract

Achieving net-zero greenhouse gas emissions is essential to meet global climate targets, and this objective cannot be realized without large-scale deployment of carbon dioxide removal (CDR), especially for the pathways limiting warming to 1.5 °C or well below 2 °C. Biochar is part of the CDR portfolio that has a potential for a long-term carbon storage and the provision of environmental co-benefits that go beyond the carbon dioxide removal. Scaling up this technology requires an extensive understanding of aspects including feedstock availability. Fundamental geological and industrial datasets required for spatially explicit analyses are often incomplete or imprecise, limiting the robustness of current assessments of CDR feedstock availability. Moreover, projections of how sustainable feedstock availability may evolve under future climate scenarios are not sufficiently explored by existing research. As a result, a significant knowledge gap persists in the consistent global characterization and spatial mapping of feedstocks for biochar, particularly with respect to its potential shifts under future climate scenarios, underscoring the need for targeted research to address these limitations.

The goal of this research is to quantify and compare the country-level availability of key feedstocks for biochar production by mid-century, providing a robust basis for prospective life-cycle assessment and deployment planning. The analysis was conducted using prospective scenarios based on the extrapolation of historical trends. Our results offer a) a harmonized country-level dataset of the projected sustainable feedstock availability, b) global maps and rankings illustrating spatial patterns and relative potentials, as well as c) the identification of regions where different CDR portfolios may be most effectively supported in a sustainable way by locally available feedstocks.

Keywords: Biochar, CDR, Sustainable Feedstock, Net-zero, Carbon Dioxide Removal.

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1. INTRODUCTION

1.1. The Need for Carbon Dioxide Removal in the Net-Zero Transition

The international community, guided by the Paris Agreement, has established the critical objective of limiting global warming to well below 2 °C and pursuing aggressive efforts to limit the temperature increase to 1.5 °C above pre-industrial levels (Chiquier et al., 2022; Kern et al., 2025). While decarbonization across energy, industrial, and transport sectors remains the primary lever for climate mitigation, emission reductions alone are insufficient (Ampah et al., 2024). Achieving absolute zero emissions is technologically and economically improbable due to "hard-to-abate" sectors such as heavy manufacturing, aviation, and agriculture (Agbo et al., 2024; Fuhrman et al., 2023; Powis et al., 2023; Minx et al., 2024). Consequently, the large-scale integration of Carbon Dioxide Removal (CDR) often referred to as Negative Emission Technologies (NETs) is widely recognized as a necessity (Ampah et al., 2024; Mignone et al., 2024; Fuhrman et al., 2023; Powis et al., 2023). CDR encompasses an array of anthropogenic activities designed to extract carbon dioxide (CO₂) directly from the atmosphere and/or biogenic sources and durably store it. Its strategic implementation is required across all time horizons: accelerating near-term emission reductions, counterbalancing medium-term residual emissions from hard-to-abate sectors, and ultimately generating the net-negative emissions required to reverse historical temperature overshoots (Powis et al., 2023; Calvin et al., 2023; Minx et al., 2024; Thompson et al., 2025). Currently, there is a disconnection between modelled requirements and reality. While models suggest that 7 to 10 billion tons of CDR per year will be needed by 2050, novel engineered methods account for merely ~2 million tons of removal annually (Powis et al., 2023; Minx et al., 2024). This mismatch between modelled demand and current deployment underscores the scale of the challenge ahead. While a diversified CDR portfolio will be essential for climate stabilization, it cannot substitute for rapid decarbonization; instead, sustainable climate pathways must combine large gross emission reductions with the careful scaling of CDR under appropriate regulatory, environmental, and social safeguards. (Fuhrman et al., 2023; Otto and Matzner, 2024; Minx et al., 2024).

1.2. Biochar and the Circular Bioeconomy

The portfolio of CDR strategies is diverse, varying significantly in their technological readiness, costs, and scalability (Calvin et al., 2023; Minx et al., 2024). While methods like Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DACCS) face technological and financial hurdles, and Afforestation (AR) requires land-use changes, biochar has rapidly emerged

as a versatile, technologically mature alternative. Produced via the thermochemical conversion (pyrolysis) of organic biomass under oxygen-limited conditions, biochar is a stable, carbon-dense material capable of storing carbon in soil for centuries (Zilberman et al., 2023; Saldarriaga and López, 2025; Siddiqui, 2025; Lehmann et al., 2021).

Due to its high specific surface area, low bulk density, and strong adsorption capacity, biochar has the potential to function as a bridge between renewable energy generation, sustainable agriculture, and climate change mitigation (Siddiqui, 2025; Mensah et al., 2025). It has been shown to offer co-benefits, including (but not limited to) improved soil structure, enhanced water retention, and reduced reliance on synthetic fertilizers (Saldarriaga and López, 2025).

From a carbon accounting and life-cycle perspective, climate benefits of biochar are multifaceted: it has the potential to provide durable carbon sequestration in soils; it may alter microbial pathways to suppress the emission of potent non-CO₂ greenhouse gases, such as nitrous oxide and methane; it co-produces energy carriers (bio-oil and syngas) that can substitute fossil fuels; and it can support avoidance of decomposition emissions that would occur if the source biomass were left to decompose in landfills or lagoons (Lehmann et al., 2021; Woolf et al., 2010; Zilberman et al., 2023; Pavesi et al., 2024; Saldarriaga and López, 2025; Siddiqui, 2025). By integrating waste management with durable sequestration, biochar shows potential in offering a holistic and cost-effective CDR pathway (Panwar et al., 2019; Phiri et al., 2024; Saldarriaga and López, 2025). However, the utilization of biochar depends on the availability of sustainable biomass feedstocks. To avert the socio-environmental externalities associated with purpose-grown energy crops, such as competition for arable land, exacerbation of global food insecurity, biodiversity loss, and land-use change (LUC) emissions, sustainable biochar production must rely on existing biological byproducts (Feng and Rosa, 2024; Woolf et al., 2010). This necessity aligns with the principles of a Circular Bioeconomy, which dictates that biological resources must be managed within strict planetary boundaries, prioritizing local soil health and food security over energy generation (Lefebvre et al., 2023; Stellingwerf et al., 2022; Marin et al., 2025; Saldarriaga and López, 2025; Siddiqui, 2025).

Within this framework, it is critical to methodologically distinguish between organic waste and ecological residues. Organic waste refers to post-consumer or end-of-pipe refuse (such as municipal solid waste, wastewater biosolids, and livestock manure) that requires active management to mitigate environmental hazards. Conversely, residues refer to the leftover plant matter from agricultural harvests (e.g., stalks and straw) and forestry operations (e.g., branches and deadwood). Unlike waste, residues play a vital role in natural ecosystem cycles, protecting against

soil erosion and returning carbon to the earth (Tisserant et al., 2023; Liu et al., 2023). Because biochar is one of the few technologically mature CDR methods that does not intrinsically compete for arable land (Tisserant et al., 2023), the accurate assessment of how much of this residue can be safely extracted without violating ecological boundaries—alongside the total utilizable volume of organic wastes—is an indispensable component of modelling global transitions to a net-zero carbon economy by 2050.

1.3. Literature Review

Lefebvre et al. (2023) developed a global, country-level framework to estimate the carbon dioxide removal potential of biochar produced from sustainably available biomass residues. The authors combine residue supply data from agriculture, livestock, forestry, and wastewater systems with residue-to-product ratios, collection factors, pyrolysis yield assumptions, and a soil-temperature-based permanence model to quantify both technical and constrained biochar potential. Their analysis shows that biochar could make a meaningful contribution to national mitigation targets, especially in countries with strong agricultural production, while also revealing that the opportunity is highly uneven across regions. The results indicate that the largest absolute mitigation potential concentrated in major agricultural countries including China, the United States, Brazil, and India, whereas some smaller countries can offset a much larger share of their national emissions. The study also highlights that a small number of crop types often dominate national residue availability, which suggests that biochar deployment strategies should focus on the most abundant and locally important feedstocks. At the same time, the authors adopt a conservative accounting approach by retaining part of field residues for soil health and excluding several co-benefits such as avoided methane, nitrous oxide, and fossil fuel substitution. Methodologically, the paper is limited by simplified assumptions, incomplete global residue data for some biomass streams, and uncertainty in feedstock conversion and permanence parameters. Future work should focus on more detailed country-specific residue inventories, updated conversion factors, and integrated assessments that combine biomass availability, logistics, economics, and policy conditions.

Karan et al. (2023) developed a global, spatially explicit assessment of crop residue availability and converted it into estimates of technical and constrained biochar carbon sequestration potential using residue-to-product ratio models, gridded crop production data, and empirical equations for biochar yield and permanence. Their results show that crop residues produce about 2.4 Pg C per year globally, with cereals contributing the largest share, especially maize, rice, and wheat residues. If all residues were used, the technical biochar potential would reach about 1.0 Pg C per year, but when sustainable harvesting limits and competing uses such as livestock fodder are considered,

this falls to about 0.51 Pg C per year, with about 0.36 Pg C per year remaining sequestered after 100 years. The study also shows strong spatial heterogeneity, with the largest total potentials concentrated in China, the United States, India, Brazil, and Argentina, while some countries such as Bhutan, India, Ghana, Bulgaria, Rwanda, and Malawi could offset a large share of their national emissions. Methodologically, the paper is valuable because it uses high-resolution global crop maps rather than coarse national averages, which improves the spatial realism of residue estimates. The authors also correct for unrealistically high yield outliers in the gridded data and apply crop-specific residue-to-product ratios selected from the literature using criteria such as publication date, sample size, uncertainty, and goodness of fit. The residue availability estimates depend on crop-yield downscaling and residue-to-product ratios, both of which carry uncertainty and are not fully quantified. The authors also use conservative assumptions about residue retention, excluding part of the biomass to protect soil health and accounting for competing livestock uses, which lowers the estimated accessible feedstock. In addition, the paper does not provide a full life-cycle assessment, so emissions from harvesting, transport, conversion, and possible avoided emissions are only partially represented. The main takeaway is that biochar from crop residues has meaningful but highly uneven mitigation potential, and that realistic resource assessment must distinguish between theoretical supply and sustainably available supply. The paper also implies that future work should improve residue retention rules, update crop-specific models, and better quantify how biochar application may allow greater sustainable residue removal without harming soil functions.

Sileshi et al. (2025) introduced the Organic Matter Database (OMD) as the first global effort to consolidate residue and by-product data from agriculture, fisheries, forestry, and related industries. Its main goal is to provide standardized definitions, typologies, and methods for estimating and reporting organic residues, while also generating regional and global estimates of materials potentially available for use in a circular bioeconomy. The motivation is that residues and by-products are often poorly quantified, inconsistently classified, and underused, despite their relevance for soil amendment, livestock feed, bioenergy, and pollution reduction. Methodologically, the OMD is built from FAOSTAT and FishStatJ data, supplemented with nutrient-concentration data from existing databases, IPCC defaults, and scientific literature. The authors define clear categories for crop residues, agro-processing by-products, livestock manure, and forestry residues, and they explicitly exclude waste streams where local legal definitions and management differ too widely. For estimating quantities, they rely on IPCC and FAO conversion methods, residue-to-product relationships, country-specific extraction, or take-off rates where available, and bootstrapping to express uncertainty for some estimates. The database is reported

at the national level and is designed to be updated continuously as new production data become available. The results show that residues and by-products are produced in exceptionally massive quantities globally, but with strong regional variation. Among crop residues, maize, wheat, and rice dominate global production. The paper also shows that livestock manure is especially abundant, with non-dairy cattle producing the largest share, and wood residues are substantial but underestimated because data are incomplete for many countries. Overall, the OMD demonstrates that a large biomass resource base exists, but that availability for soil amendment or recycling is limited by competing uses and transport constraints. The paper's main limitations are the lack of country-specific conversion factors, incomplete statistics for many residue streams, and the inability to estimate all residues across agriculture, fisheries, and forestry with uniform accuracy. The authors also note that they could not fully account for residues processed outside their country of origin, nor provide uncertainty estimates for many national and subnational values because of missing data. Accordingly, future studies should focus on refining biomass inventories at finer spatial scales, developing country-specific conversion equations, enhancing the documentation of competing uses, and producing spatially explicit maps of residue-derived carbon and nutrient resources.

Mensah et al. (2025) estimated the global sustainable bioenergy potential from waste and residue biomass up to 2050, while excluding energy crops because of sustainability concerns. It also aims to fill gaps in the literature by providing a first open-access global-national database with 5-year temporal resolution. Methodologically, the study develops the LUT-Bioenergy model and combines FAO crop and livestock projections, FAO forestry statistics, World Bank municipal solid waste data, and UN population projections. It estimates four main sustainable bioenergy categories: crop residues, biogas from livestock manure/humanure/organic biowaste, forestry residues, and municipal solid waste, using scenario-based assumptions under Business-as-Usual and Towards Sustainability pathways. This study uses collection efficiencies, residue-to-product ratios, lower heating values, and scenario-specific growth trends to convert biomass quantities into energy potentials at global-national resolution from 2015 to 2050 in 5-year steps. The results show that by 2050 the total sustainable bioenergy potential reaches 33,183 TWh/yr in the Business-as-Usual scenario and 24,288 TWh/yr in the Towards Sustainability scenario. Crop residues dominate the total potential, contributing 18,022 TWh/yr in BAU and 16,786 TWh/yr in TSS, followed by forestry residues, municipal solid waste, and biogas. Regionally, South Asia, Northeast Asia, and sub-Saharan Africa are the largest contributors in the BAU case, while Northeast Asia, South Asia, and Europe dominate under the TSS scenario. The paper argues that sustainable biomass can supply a substantial share of future energy demand and support the transition away from fossil

fuels. The main limitations are that the model does not include climate change impacts on agricultural and forest productivity, does not estimate energy return on energy invested, and assumes that key variables remain constant over time. Future work should improve the model by incorporating country- and year-specific residue generation coefficients, collection efficiencies, and energy use factors. More broadly, they suggest that future studies should expand the biomass sources included in the model and further refine the geographic resolution of sustainable biomass data.

Jacobson and Jones (2025) map and synthesize international biomass supply assessments into a citable, harmonized, and updateable global repository that helps answer whether sustainable biomass exists. It also aims to provide guidelines for improving future biomass assessments and making them more comparable across countries. Methodologically, the authors use a bottom-up approach based on publicly available reports and datasets submitted by national stakeholders, complemented by international and academic sources. They reviewed sixty-five reports, of which twenty-nine were included in the database, covering sixty-two countries for current estimates and forty-one countries for 2030 projections. They then harmonized biomass resource names, units, and classifications using a centralized database and a resource ontology aligned with the Bioenergy KDF structure. They also assessed how sustainability was defined and operationalized in each report, using a seven-factor matrix covering biomass resource limits, soil and water quality, water use, land use, biodiversity, GHG emissions, and growth/yield. The results show that the current estimates from the sixty-two countries sum to 2.83 billion dry metric tons of sustainable biomass, with the largest volumes in the Americas, followed by Europe, Asia, and Africa. Brazil and the United States are the largest contributors, and the forty-one countries with 2030 projections indicate a rise from 1.32 to 2.13 billion dry metric tons, or about a 60% increase. The report also finds that most of the available data is concentrated in Europe and the Americas, while Africa and the Middle East remain underrepresented. In addition, the study standardizes 349 reported biomass resource names into 105 categories, making cross-country aggregation more feasible. The main limitations are incomplete global coverage, uneven geographic representation, and major inconsistencies in terminology, units, sustainability criteria, and reporting detail across source studies. The dataset is also incomplete because it only includes non-proprietary, publicly shareable sources and does not yet reflect a comprehensive global biomass inventory. Many reports also lack clear documentation of sustainability assumptions, conversion factors, or the economic feasibility of supply. Future work should focus on building a more complete global repository, expanding country coverage, and periodically updating the database as new reports become available. The authors recommend stronger standardization of biomass naming, measurement, sustainability

criteria, and techno-economic analysis in future assessments. They also call for more transparent and comparable reporting that includes the economic, social, and environmental dimensions of sustainability.

Ampah et al. (2024) assess how Africa can reach net-zero emissions by 2050 using land-based carbon dioxide removal strategies, with a focus on afforestation/reforestation, BECCS, and biochar. It specifically examines the trade-offs and synergies of these options for Africa's energy, land, water, food, and emissions systems. Methodologically, the authors use the GCAM 5.4 integrated assessment model and impose a continental net-zero CO₂ pathway in which emissions peak before 2025 and decline linearly to zero by 2050. They model four scenarios: all three CDR options together, afforestation/reforestation only, afforestation/reforestation plus BECCS, and afforestation/reforestation plus biochar, all under the SSP2 baseline. The model treats non-CO₂ gases through marginal abatement cost curves and applies a carbon price from 2025 onward to land-use, fossil-fuel, and industrial CO₂ emissions. The main results show that by 2050, total gross carbon removal reaches about 1.2 GtCO₂ per year when all three CDR approaches are available, compared with about 0.5 GtCO₂ per year for afforestation alone. The study also finds that deploying multiple CDR strategies lowers staple food prices relative to AR-only, but BECCS increases water demand and can intensify pressure on land and food systems, especially in Southern Africa. Regionally, Western Africa becomes in the model the largest contributor to carbon removal, while Northern Africa contributes the least. The authors imply the need for further work on better integrating CDR with food-security and water-security constraints, especially at the regional level. They further suggest that future IAM studies should distinguish more clearly between decarbonization and carbon removal so that CDR complements rather than substitutes emissions cuts.

1.4. Research Gaps

1. There is no integrated global framework that jointly projects crop yield, harvested area, industrial wood, and livestock populations in 2050 and then converts those projections into residue availability using consistent methods across all countries. Most residue studies focus on current or near-term biomass availability, not 2050 projections based on historical trends and time-series forecasting.
2. Although many studies estimate biomass technical potential, fewer quantify the sustainably constrained supply after removing biomass needed for competing uses including animal feed and bedding and soil retention. In addition, competitive industry allocation (Sustainable Aviation Fuel, Chemicals & plastics) is often inconsistent across studies,

making it difficult to compare how residues are available for bioenergy, biochar, and other applications.

1.5. Research Questions

1. What will the global country-level sustainable availability of crop residues, forestry residues, and manure be under future (2050) time horizon from historical FAOSTAT data?
2. How do projected 2050 residue supplies vary across countries after accounting for competing uses in agriculture, forestry, and manure sectors?
3. Which biomass stream contributes the largest share of constrained residue availability in 2050: agriculture, forestry, or manure?
4. Which countries show the highest surplus residue potential for biochar after accounting for competing uses?

1.6. Research Objectives

1. Compile and harmonize global data: To standardize disparate agricultural and biomass datasets into a unified, consistent global baseline.
2. Quantify sustainable residues: To estimate country-specific biomass harvesting potential under sustainable conditions that preserve local ecosystems.
3. Identify key drivers: To pinpoint the dominant feedstocks and specific nations that contribute most to global biomass availability.
4. Determine biochar potential: To calculate the final global capacity for sustainable biochar production based on quantified residues and identified regional drivers.

2. METHODOLOGY

This chapter outlines the analytical framework, data processing techniques, and modelling approaches employed to forecast global biomass residue availability and its subsequent biochar production potential in 2050. To provide accurate and realistic projection, the methodology transitions beyond gross theoretical calculations by systematically integrating dynamic constraints, such as ecological retention requirements and the demands of competing bio-economies. To ensure consistency across all feedstock categories, uniform definitions were adopted for both theoretical and available residues. Theoretical Biomass Potential (TBP) refers to the maximum quantity of residues that can potentially be generated from each feedstock category. Available Biomass Potential (ABP) refers to the quantity of residue remaining after accounting for competing uses and industrial demand for each feedstock. To capture a comprehensive picture of the global biomass landscape, this study analyses three distinct primary feedstock sectors including agriculture, forestry, and manure. Each sector possesses its generation mechanics, competing usages, and biochar conversion efficiencies. For agriculture biomass, this study focuses on major global cereal crops, which account for the majority of harvestable agronomic biomass. The specific feedstock models include primary field-based straws (wheat straw, rice straw, maize straw, millet straw, barley straw, sorghum straw, and other miscellaneous cereal straws) and processing byproducts (rice husks and maize cobs). Forestry residues comprise the unmerchantable woody biomass left over from timber harvesting and silvicultural operations. Rather than treating forestry as a single aggregate source, this study isolates residues based on specific forest management scenarios, reflecting the diverse ways timber will be harvested globally in 2050. The sources include:

- **Clear-Cut Residues:** Biomass (tops, branches, and unmerchantable stems) left on-site following the complete removal of a forest stand.
- **Selective Cut Residues:** Biomass generated from continuous-cover or partial-harvesting systems, which typically yield less residue per hectare but are increasingly common under sustainable management policies.
- **Wood Plantation Residues:** Intensive, short-rotation forestry operations specifically managed for high-yield timber or pulp.
- **Processing Residues:** Sawdust, bark, and offcuts generated at sawmills and timber processing facilities including wood chips and particles.

Finally, livestock manure serves as a concentrated, nutrient-rich feedstock for biochar production. The volume of this feedstock is driven by 2050 livestock population forecasts and species excretion rates. The distinct animal categories analyzed in this study include dairy cattle, non-dairy cattle, buffalo, horses, sheep, goats, chickens, and swine. Table 1 outlines the foundational datasets, parameters, and sources used to establish historical production baselines for the biomass feedstocks analyzed in this study. It details the scope of the raw data that serves as the starting point for subsequent residue and biochar projections.

Table 1. Feedstock data and sources.

Feedstock	Feedstock Category	Element	Geographic Coverage	Time Period	Data Source
Agriculture	Wheat, Maize, Sorghum, Millet, Barley, Rice, Cereals n.e.c.	Crop yield, Area harvested	All countries where data is available	1990-2024	FAOSTAT
Forestry	Other industrial roundwood (coniferous, non-coniferous), Pulpwood, round and split (coniferous, non-coniferous), Sawlogs and veneer logs (coniferous, non-coniferous), Wood fuel (coniferous, non-coniferous), Wood chips and particles, Wood residues	Production			FAOSTAT, IMAGE 3.2, KNMI (Royal Netherlands Meteorological Institute)
Manure	Cattle (dairy, non-dairy), Buffalo, Horses, Sheep, Goats, Chickens, Swine	Stocks, Amount excreted in manure (N content), Manure applied to soils (N content), Manure management (manure treated, N content)		1990-2023	FAOSTAT

2.1. Agricultural Residue and Biochar Potential Forecasting in 2050

2.1.1. Setting, Scope, and Data Sources

This methodology estimates agricultural cereal-residue generation and the residue feedstock remaining for biochar production in 2050. It is based on country-level forecasting of harvested area and crop yield, calculation of theoretical residue using residue-to-product ratios, forecasting of country-level residue-use shares, and subtraction of fixed competing industrial demand shares. The study's geographical coverage is global and includes all countries available in the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT). The temporal scope ranges from historical baseline data between 1990 and 2024, to project of this data in the year 2050. The modelled target crop categories are cereals especially maize, rice, wheat, barley, sorghum, millet, and other cereals. The target elements used to calculate agricultural residue are crop yield (kg ha^{-1}) and harvested area (ha). In addition, there is another data source providing detailed gridded inventories of cereal crop residue allocations from 1997 to 2021. A separate gridded NetCDF dataset of crop-residue production and residue-use categories is used to derive historical national shares of burnt residues, animal usage, other usage, and residues left on field. The gridded data are spatially joined to country boundaries from Natural Earth and aggregated to country-year totals (Smerald et al., 2023).

2.1.2 Forecasting Harvested Area and Crop Yield in 2050

To estimate agricultural residue production at the country and crop level in 2050, two separate forecasting pipelines were developed: one for harvested area (ha) and one for crop yield (kg ha^{-1}). Both pipelines share an identical modelling framework based on Error-Trend-Seasonal (ETS) exponential smoothing, applied independently to each country–crop combination. ETS models were selected for their well-established performance on annual agricultural time series, their ability to manage non-linear growth trends through multiplicative error specifications, and their native provision of probabilistic prediction intervals.

2.1.2.1. Data Preprocessing and Standardization

First, data for area harvested and crop yield metrics extracted from FAOSTAT. To ensure statistical precision in forecasting, we applied a strict rule of at least twenty valid historical data points per pair. Any country or crop group that did not pass this check was excluded. To deal with gaps, we constructed continuous yearly time series for each group. Missing values were filled with linear interpolation method, and extreme outliers are mitigated using an Interquartile Range (IQR) method for the two datasets, with a multiplier of 3.0. Values outside the interval were clipped to the respective fence, with a hard lower bound of zero to prevent physically impossible negative values. An additional guard was applied to the forecast horizon. Series observed last year were

more than 50 years before the target year of 2050 were excluded to prevent unreliable long-range extrapolation in data-sparse contexts.

2.1.2.2. Selecting Models and Validating Results

Because agricultural expansion and crop productivity eventually saturate due to geographical constraints and biological maxima, an ETS model was chosen for both variables. To capture underlying agricultural trajectories, the models incorporate additive trends with dynamic damping. This is where the damp parameter comes into play. It naturally flattens the trend line at longer horizons, avoiding the unrealistic infinite growth that is often projected by standard linear models. The algorithm iteratively evaluates both additive and multiplicative error structures (ETS (A, A, N) and ETS (M, A, N)), selecting the optimal configuration based on the minimization of the Akaike Information Criterion (AIC). Prior to developing the final 2050 projections, predictive accuracy was validated with an out-of-sample holdout approach. Dynamic holdout validation set (representing approximately 20% of the temporal observations), assessed using Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and Prediction Interval Coverage Rate.

2.1.2.3. FAO-Anchored Growth Cap

To prevent forecasts from diverging unrealistically beyond the bounds of consensus global agricultural projections, crop-specific growth caps were applied and derived from World agriculture towards 2030/2050: the 2012 revision report (Alexandratos and Bruinsma, 2012). The base reference value for each country–crop series was computed as the average observed value over the 2005–2007 period. If data were unavailable for that window, the first three available observations were used as a fallback.

The growth cap was defined as:

$$\text{Area Cap} = \text{Mean Area}_{2005-2007} \times \phi_{\text{crop}} \quad \text{eq.1}$$

$$\text{Yield Cap} = \text{Mean Yield}_{2005-2007} \times \phi_{\text{crop}} \quad \text{eq.2}$$

Where ϕ_{crop} is the FAO crop-specific multiplier (Table 2). Area multiplier is a coefficient represents the projected relative change in the total physical harvested land area dedicated to a specific crop compared to a baseline year. The yield multiplier is a coefficient that represents the expected relative increase in crop productivity. For harvested areas, multipliers range from 0.981 (rice) to 1.252 (maize), reflecting the FAO projection that most crop expansion to 2050 will be driven by yield growth rather than area expansion. For yield, multipliers range from 1.2 to 1.56, reflecting projected crop improvement trajectories. A default multiplier (average value for crops) of 1.117 (area) and 1.36 (yield) was applied to other cereals (Cereals n. e. c.).

Table 2. FAO crop-specific growth multipliers.

Crop	Area multiplier	Yield multiplier
Wheat	1.014	1.357
Rice	0.981	1.3
Maize	1.252	1.3
Barley	1.143	1.2
Sorghum	1.178	1.46
Millet	1.135	1.56
Cereals n.e.c.	1.117	1.36

2.1.2.4. Post-Processing: Yield Adjustment for Dry Matter

Agricultural yields in global macroeconomic databases (e.g., FAOSTAT) are reported in “fresh weight” or “as-harvested” weight, with large and highly variable moisture content depending on crop species and local harvesting practices. These projected fresh yields need to be adjusted for water weight to arrive at accurate measures of absolute biomass and energy potential, and volumes of crop residues. After forecasting the crop yield, an additional post-processing conversion step was employed to standardize the projected raw yields into dry-matter basis for residue production estimation. Each crop-specific dry-matter conversion factor (Table 3) was applied to the 2050 yield forecast and its prediction interval bounds. The mathematical transformation is as follows:

$$Yield_{dry} = Yield_{fresh} \times DWCF_{crop} \quad \text{eq.3}$$

Where:

$Yield_{dry}$: The projected dry weight yield of the crop in the year 2050. This measures the actual solid biomass of the harvest with all water content completely removed.

$Yield_{fresh}$: The projected fresh weight (or wet weight) yield of the crop in the year 2050. This is the total mass of the crop immediately after harvest, which includes its natural moisture content.

$DWCF_{crop}$: The Dry Weight Conversion Factor (DWCF) for the specific crop. This is a standard ratio (a number between 0 and 1) representing the fraction of the fresh crop that is dry matter. The crop-specific DWCF parameters used in this study were obtained from (Yu et al., 2020). By applying these static scalar coefficients to the 2050 projections, the methodology ensures future biomass estimates are biophysically consistent with current crop profiles.

Table 3. Dry weight conversion factors for different crop residues.

Crop Residue	Dry Weight Conversion Factor [-]
Maize straw	0.87
Maize cob	0.87
Wheat straw	0.88
Rice straw	0.90
Rice husk	0.90
Barley straw	0.88
Other cereals	0.88
Millet Straw	0.9
Sorghum Straw	0.88

2.1.2.5. Quantification of Residue-to-Product Ratios (RPR)

One important consideration for the proper estimation of agricultural residue is that the Residue-to-Product Ratio (RPR) is not constant in all levels of productivity. RPR is a standard, dimensionless metric used to estimate how much "leftover" plant material (biomass) is generated in relation to the primary crop that is harvested for food or sale. With the optimization of agricultural systems for higher crop yields, a higher fraction of the biological energy and mass of the plant is devoted to the grain, as opposed to the vegetative components (i.e. the harvest index increases). To take this biological reality into account, the calculation of RPR was divided into two different modelling approaches depending on the residue type: primary field residues are modelled dynamically based on fluctuating crop yields and secondary processing residues are calculated using fixed, static multipliers (Table 4 and 5 and see sections 1 and 2 of Appendix for the detailed calculations).

Table 4. Empirical coefficients.

Type of Residue	Crop Residue	a	b	Source
Primary (Field-based)	Wheat straw	2.183	-0.127	Bentsen et al., 2014
	Maize straw	2.656	-0.103	
	Barley straw	1.822	-0.149	
	Rice straw	2.45	-0.084	
	Other cereals straw	1.88	-0.12	Ronzon and Piotrowski, 2017
	Sorghum Straw	2.302	-0.1	
	Millet Straw	1.904	-0.21	Smerald et al., 2023

Table 5. Static RPR.

Type of Residue	Crop Residue	Constant RPR	Source
Secondary (Processing)	Maize cob	0.273	Koopmans and Koppejan, 1997
	Rice husk	0.267	

2.1.2.6. Quantification of Theoretical Agricultural Residue Potential

After the derivation of the RPR (derived dynamically and statically), the final theoretical agricultural residue biomass was quantified for the target year 2050. The term “theoretical potential” in the context of biomass assessment literature is the maximum biophysical mass of vegetative matter produced by the agricultural system prior to the application of technical harvesting constraints, ecological retention needs, or competing economic usages. This phase was a mathematical combination of the spatial parameters (harvested area) and agronomic parameters (dry yield), predicted independently with their respective biomass allocation ratios. To estimate the total absolute mass of residue generated by each crop within a given country, the established RPRs were applied directly to the total projected dry mass of the harvest. This approach operates on the fundamental principle that theoretical residue is the product of the land area under cultivation, the productivity of that land, and the biological proportion of vegetative matter to harvested grain. The theoretical residue potential was calculated using the following deterministic equation:

$$TBP_{c,i,2050} = A_{c,i} \times Y_{dry,c,i} \times RPR_c \quad \text{eq.4}$$

Where:

- $TBP_{c,i}$ is the Theoretical Biomass Potential for a specific crop (c) in a specific country (i), expressed in total Mg year⁻¹.
- $A_{c,i}$ is the projected 2050 area harvested for the crop (in hectares), as derived from the time-series forecasting models.
- $Y_{dry,c,i}$ is the projected 2050 crop yield (in Mg ha⁻¹), standardized to dry matter weight.
- RPR_c is the dimensionless Residue-to-Product Ratio (whether applied as a deterministic static multiplier or a dynamic, yield-adjusted exponential variable) specific to the crop and residue fraction.

The product of area (ha) and yield (kg ha⁻¹) gives a total mass in kilograms, so the denominator of 1000 is a simple conversion of units. This standardizes the result to Megagrams (Mg, or metric tons), the common macro-scale unit in regional and global biomass assessments. The output is rounded to two decimal places and saved by country and crop-residue type.

2.1.3. Quantification of Available Agricultural Residue for the Emerging Bioeconomy

While the Theoretical Biomass Potential (TBP) quantifies the absolute maximum biophysical mass of vegetative matter generated, it does not reflect the realistic volume of biomass accessible for novel industrial uses. Agricultural residues are deeply embedded within complex local socio-ecological and economic systems. Historically, large fractions of this biomass are used for competing purposes including livestock feeding and bedding, residential combustion for heating and cooking, or being intentionally left on the field to replenish soil organic carbon, retain moisture, and prevent erosion (Ebadian et al., 2021; Bioenergy for the Energy Transition, 2022; Intergovernmental Panel On Climate Change (IPCC), 2023). Consequently, only a specific residual fraction, categorized in this study as "other uses" (representing surplus or economically mobilizable biomass), can be sustainably diverted to support emerging, high-tech bioeconomy applications such as biochar production. The methodology accurately estimates this available biomass in 2050 by using the historically determined residue partitioning behavior. Historical crop residue management was taken from the spatially explicit dataset produced by Smerald et al., (2023) to empirically quantify the proportion of biomass allocated to the competing pathways. As the dataset is available at a gridded scale with high resolution, a geographical transformation was needed to fit the dataset into the macroeconomic, country-level forecasting framework of this study.

2.1.3.1. Forecasting Residue Usage Shares (Compositional Analysis)

To estimate the future distribution of crop residue utilization (burnt residues, animal usage, left on field, and other usage) out to the year 2050, a compositional time-series forecasting framework was developed. The various applications of crop residues are compositional data that collectively make up a fixed total; therefore, standard independent forecasting approaches can produce projected shares that fail to sum to 100%. To overcome this "unit closure" problem, this study employed Additive Log-Ratio (ALR) Transformations combined with ETS models. The ALR transformation is a mathematical technique used in statistics to safely and accurately analyze compositional data. Introduced by statistician John Aitchison in 1986, it is a standard method for converting "closed" data (like percentages or proportions) into standard, unconstrained data so that normal statistical tools can be applied without causing mathematical errors. The methodology consisted of four primary phases:

Phase 1: Spatial Aggregation and Data Cleaning

Historical data on crop residue production and their specific use were obtained from gridded spatial datasets (NetCDF format). To ensure data quality, an algorithmic cleaning step was used to

identify and mask “isolated zeros” – years in which a usage dropped to zero temporarily between active years, which usually indicates missing reporting rather than a true cessation of a practice.

Phase 2: Compositional Transformation (ALR)

To prepare the usage data for predictive modelling, the absolute tonnages for each usage category were first converted into a compositional share (percentage of total usage). Then an ALR transformation was applied. This approach translates the constrained compositional shares (which must sum to exactly 1.0) into an unconstrained, continuous mathematical space.

Phase 3: Time-Series Forecasting and Uncertainty Quantification

Once transformed into the ALR space, the historical trends were modelled using a univariate ETS algorithm. A damped trend was deliberately selected to simulate realistic long-term saturation, preventing the model from projecting infinite linear growth over the 29-year forecast horizon.

Phase 4: Inverse Transformation and Final Quantification

In the last step, the predicted ALR values for 2050 were transformed by an inverse-ALR mathematical transformation. This required the unrestricted projections to be brought back into legitimate compositional shares, so that the projected percentages of residue use summed to exactly 100% in each country. Finally, these projected shares were multiplied with the independently forecasted total crop residue production to obtain the absolute projected mass (in Mg) assigned to each usage category in 2050.

Finally, the absolute amount of available crop residue that could be used as feedstock for industries in 2050 was calculated as the product of the projected $TRP_{c,i,2050}$ and the country's projected “other usage” share ($S_{oth,2050}$). Mathematically, this relationship can be written as:

$$NAB_{c,i,2050} = TBP_{c,i,2050} \times S_{othe,i,2050} \quad \text{eq.5}$$

Where:

- $NAB_{c,i,2050}$ represents Net Available Biomass for crop c in country i in 2050, expressed in dry metric tons (Mg year⁻¹).
- $TBP_{c,i,2050}$ represents the forecast Theoretical Biomass Potential derived from projected area harvested, crop yield, and biophysical Residue-to-Product Ratios (RPR).
- $S_{other,i,2050}$ represents the forecasted Other Usage Share (the predicted percentage of biomass not consumed by livestock, retained on fields, or combusted domestically).

By applying this socio-ecological discount factor to the theoretical baseline, the resulting NAB metric provides a highly realistic, geopolitically adjusted, and biophysically constrained inventory of the biomass genuinely available for next-generation carbon sequestration technologies. Last step estimates a minimum and maximum net residue feedstock remaining for biochar after deducting

fixed shares for competing industrial uses. The method uses a low-competition share of 0.075 and a high-competition share of 0.119, representing the aggregated minimum and maximum shares assigned to aviation and plastics/chemicals demand (see section 3 in Appendix). The calculations are:

Maximum residue availability for biochar production (Low Industrial Competition):

$$ABP_{max} = NAB_{c,i,2050} \times (1 - S_{comp,low}) \quad \text{eq.6}$$

Minimum residue availability for biochar production (High Industrial Competition):

$$ABP_{min} = NAB_{c,i,2050} \times (1 - S_{comp,high}) \quad \text{eq.7}$$

Where:

ABP is Available Biomass Potential, and S_{comp} is cumulative competitive share.

The maximum value corresponds to the lower competing-demand scenario, while the minimum value corresponds to the higher competing-demand scenario. These values are residue feedstock quantities available for the biochar pathway. They should not be interpreted as produced biochar mass. Produced biochar mass is calculated only in a separate step.

2.2. Manure and Biochar Potential Forecasting to 2050

The primary data for this section were obtained from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT). Historical datasets covering the period 1990–2023 were retrieved for eight livestock categories: buffalo, cattle (dairy, non-dairy), sheep, goats, horses, swine, and chickens. The data included animal population counts (stocks), Amount excreted in manure (N content), Manure management (manure treated, N content), and Manure applied to soils (N content). The uncertainty associated with livestock populations will vary widely depending on source but should be known within $\pm 20\%$. The uncertainty in default values for excretion rate estimates is $\pm 50\%$ (IPCC, 2019). The estimation of livestock manure availability for biochar feedstock in 2050 was conducted through a five-step computational pipeline. This workflow does not directly convert all manure feedstock into produced biochar mass in the main calculation. Instead, it first estimates theoretical wet manure, available wet manure, dry manure, and calculates final biochar feedstock potentials under variable loss scenario.

We first establish the projected biological baseline by forecasting the population (headcounts) of specific livestock categories in the year 2050. Historical livestock headcount data is standardized to a regular annual frequency. Geopolitical anomalies and obsolete territories (e.g., USSR, Yugoslavia SFR) are removed to maintain modern geographic consistency. To keep the

mathematical soundness of the forecasting models, data for each unique country-livestock combination is conditioned for structural data density threshold. This is to ensure statistical reliability and is achieved via a strict filter which only selects series with a minimum threshold of historical data points (set to 20 non-null observations). Missing values in the synchronized timeline are filled using linear interpolation. This is done prior to outlier corrections to avoid the extreme historical anomalies from affecting the interpolated values. Anomalies and data entry spikes are suppressed using the Interquartile Range (IQR) method. Any points outside the standard boundary are clipped at the upper threshold and a strict physical boundary of zero is applied to prevent negative production values. Future population was projected in the year 2050 using an ETS model. The algorithm iteratively tested models with additive trends (damped and undamped) against both additive and multiplicative error types, selecting the optimal configuration based on the lowest Akaike Information Criterion (AIC). Multiplicative errors were strictly restricted to datasets with exclusively positive values. Model validation was performed using a dynamic holdout set (approximately 20% of the time series, minimum 5 years), evaluated via Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE). To prevent mathematically unbounded projections, a macro-agronomic growth cap is enforced. Projections were constrained using livestock-specific multipliers relative to the 2006 historical baseline, representing the cumulative annual growth expected over the 44-year period from 2006 to 2050, based on the projections of Alexandratos and Bruinsma, (2012) (see Table 8 in the Appendix). Any combinations resulting in zero or blank predictions for 2050 are eliminated. Final projections and confidence intervals are checked for physical realism with a strict lower bound of zero.

2.2.1. Quantification of Total Raw Manure Production

Time-series models project demographics, not biological output. Therefore, the forecasted 2050 animal populations are converted into total physical waste volumes using species-specific metabolic multipliers.

- **Baseline Calculation:** The projected 2050 headcount for each livestock category is multiplied by a standard Specific Manure Production (SMP) rate (Table 6, Chávez-Fuentes et al., 2017; Martí-Herrero et al., 2015; Kafle and Chen, 2016), measured in $\text{kg d}^{-1} \text{hd}^{-1}$.
- **Annual Aggregation:** This daily output is multiplied by 365 to yield the total theoretical raw (wet) manure produced annually per country and species.

The total annual wet manure production was calculated for each unique combination of country (i), livestock category (l) in 2050.

$$TBP_{c,l,2050} = N_{c,l,2050} \times SMP \times 365 \quad \text{eq.8}$$

Where:

- $TBP_{c,l,2050}$ represents the Theoretical Manure Potential (expressed in Megagrams, Mg) for a given country, livestock category in 2050.
- $N_{c,l,t}$ denotes the total animal population (head count) for the corresponding spatial and temporal intersection.
- SMP is the specific daily manure production rate per animal head ($\text{kg day}^{-1} \text{ head}^{-1}$) for each of the livestock categories.
- 365 extrapolates the daily rate to an annual temporal scale.

Table 6. Specific daily manure production rate for each livestock.

Parameter	Units	Cattle	Buffalo	swine	Chicken	Sheep	Goat	Horse
SMP	$\text{kg d}^{-1} \text{ hd}^{-1}$	29	19	2.5	0.084	3	2.7	25

Theoretical manure production represents the total biological output, while practical recovery for bio-valorization pathways is constrained by current agricultural management practices. Manure deposited on pastures and unmanaged rangelands is not recoverable. Accordingly, we isolate the managed fraction of total excreted biomass in this assessment.

2.2.1.1. Competing uses

We processed the raw dataset using a systematic data processing pipeline to compute the minimum, maximum, and mean shares of available manure by country and livestock type. The methodology consisted of the following main steps:

Data Standardization and Cleaning: The raw dataset was first filtered to remove historical, aggregate, and non-standard regional classifications to ensure spatial consistency using current geopolitical boundaries. Legacy naming conventions, such as “Sudan (former),” were also standardized to present-day classifications.

Variable Isolation: The data were restructured to isolate three primary variables for each country, livestock category, and year, all measured by their Nitrogen (N) content:

1. Total amount of manure excreted.
2. Total manure managed (treated).
3. Total manure applied to soils.

Data Validation: To ensure mathematical validity, any records where the total excreted manure was reported as zero or missing were excluded from the analysis, preventing errors such as division by zero.

Calculation of Manure Shares: Using the isolated variables, the boundary and average shares of available manure were calculated as follows:

Maximum Share: Calculated as the ratio of managed manure to total excreted manure.

Minimum Share: Calculated by subtracting the manure applied to soils from the managed manure and dividing the result by the total excreted manure.

Application: The average value of these bounding shares from the most recent historical year is isolated. This Mean share is then multiplied against the 2050 Total Raw Manure to yield the Available Wet Manure, the fraction collected and accessible within regional agricultural systems.

2.2.2. Biochar Feedstock Estimation

2.2.2.1 Dry Matter (Total Solids) Content

Critical biophysical correction is required before determining biochar potential. Raw manure consists of water, which cannot be converted into biochar via thermochemical pyrolysis.

Total Solids (TS) Isolation: The strictly available wet manure is converted into solid dry mass by applying species-specific Dry Matter ratios (Table 7, measured in g TS kg⁻¹, Chávez-Fuentes et al., 2017; Martí-Herrero et al., 2015; Kafle and Chen, 2016). For example, poultry manure yields a much higher dry mass proportion (~67.8%) compared to dairy cattle manure (~16.9%).

Mass Standardization: The resulting solid biomass is converted into standard kiloton (kt) to yield the Dry Manure metric, representing the true physical feedstock available for kiln processing.

Table 7. Specific dry matter ratios.

Parameter	Units	Cattle	Buffalo	swine	Chicken	Sheep	Goat	Horse
Dry Matter (TS)	g TS kg ⁻¹	169.1	169.1	310.2	678.4	676	861.3	249.7
Volatile Solids (VS)	g VS kg ⁻¹	102.5	102.5	269.3	475	503	642.3	186.1

$$\text{Dry Manure (kt)} = \text{Available manure}_{2050}(\text{kg}) \times \text{TS} \times 10^{-9} \quad \text{eq.9}$$

2.2.2.2 Volatile Solids (VS) to TS Ratio

$$\text{VS/TS} = \frac{\text{VS (g kg}^{-1}\text{)}}{\text{TS (g kg}^{-1}\text{)}} \quad \text{eq.10}$$

This ratio represents the proportion of dry matter that is volatile (organic) solids.

2.2.2.3 Organic Matter Destruction Adjustment

During Anaerobic Digestion (AD) or natural decomposition, a portion of volatile solids is destroyed (60% of volatile solids are destroyed during AD, Aguirre-Villegas et al., 2019).

$$\text{Destroyed Organic Matter (kt)} = \text{Dry Manure (kt)} \times \frac{\text{VS}}{\text{TS}} \times 0.6 \quad \text{eq.11}$$

2.2.3. Biochar-Available Feedstock

The final biochar feedstock is the dry manure minus the destructed organic matter:

$$\text{ABP}_{2050} \text{ (kt)} = \text{Dry Manure (kt)} - \text{Destroyed Organic Matter (kt)} \quad \text{eq.12}$$

Where ABP_{2050} is the Available Biomass Potential for biochar production in 2050. This represents the stable dry matter available for biochar production after accounting for organic losses.

2.3. Forestry Residue and Biochar Potential Forecasting to 2050

Forestry residue is defined herein as the non-commercial vegetative biomass (e.g., branches, tops, stumps, and non-merchantable foliage) that remains in the forest environment following the extraction of industrial roundwood. To estimate the global theoretical potential of forestry residues available for bioeconomy applications at the national level by 2050, this study established a spatially explicit, scenario-driven, multi-stage forecasting framework. The methodological pipeline integrates historical production data harmonization, time-series forecasting, spatial biome allocation, downstream processing accumulation, and ecological retention constraints.

2.3.1. Spatial Mapping and Biome Classification

Because forest morphology and residue generation are fundamentally dictated by local ecological characteristics, the global extraction data required precise spatial classification. High-resolution gridded land cover data from the Royal Netherlands Meteorological Institute (KNMI) Data Platform was utilized to disaggregate the harvest projections. Through spatial processing, each grid cell (defined by its latitude and longitude coordinates) was mapped to its respective national administrative boundary and categorized into a specific ecological biome.

2.3.2. Data Harmonization and Biomass Conversion

The foundational dataset for primary wood production was sourced from historical volumetric data (e.g., FAOSTAT). To ensure standard comparative units, production volumes were converted

from cubic meters (m³) to dry matter mass (Mg). A regional wood basic density dataset was utilized to map specific densities to country-item pairs (see Table 4 in the Appendix).

To address data gaps, a hierarchical fallback mapping algorithm was developed:

1. **Exact Matching:** Country and specific wood item.
2. **Item Fallback:** Standardized to coniferous or non-coniferous pulpwood profiles where specific items lacked distinct density data.
3. **Geospatial Fallback:** Utilization of continent-level average densities for the specified item.

The dry mass was subsequently calculated utilizing the following relation:

$$M_{dry} = \frac{V \times \rho}{1000} \quad \text{eq.13}$$

Where:

M_{dry} is the dry wood mass in Megagrams (Mg), V is the reported volume in Cubic meter (m³), and ρ is the wood basic density in kg m⁻³. Historical and aggregated geopolitical entities (e.g., USSR, Yugoslavia) were filtered to maintain present-day national boundaries.

Process Residues (RP): Volumetric data for by-products (e.g., wood residues and wood chips & particles) is converted to oven-dry metric tons utilizing specific conversion quotients (see Table 5 in the Appendix). Missing country-level factors are similarly imputed using continental averages.

2.3.3. Time-Series Forecasting (ETS Modelling)

To project wood production and process residue generation to the target year 2050, the methodology applies Exponential Smoothing (ETS) algorithms to the aggregated country-level historical data.

- **Preprocessing:** Historical gaps are resolved via linear interpolation. Outliers are mitigated using Interquartile Range (IQR) clipping to prevent historical anomalies from skewing long-term projections.
- **Model Optimization:** The algorithm iteratively evaluates additive and multiplicative error structures (restricting multiplicative models to strictly positive series). Model selection is optimized based on minimizing the Akaike Information Criterion (AIC).
- **Physical Constraints:** Predictive performance was validated using a 20% dynamic holdout set to calculate the Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE). Physical constraints were enforced to ensure non-negativity in the 2050 projections.

2.3.4. Mathematical Calculation of Forestry Residues

The volume of primary residue generated during a logging event is highly dependent not only on the ecological biome but also on the specific silvicultural management practice employed. To calculate TBP, the 2050 forecasted wood production was multiplied by specific residue ratios (see Table 6 in the Appendix). These ratios characterize the proportional relationship between the extracted commercial wood and the leftover residual biomass under three distinct management paradigms: Clear Cut, Selective Cut, and Wood Plantation. The calculation is defined by the following equation:

$$TBP_{i,b,m} = H_{i,b,m} \times R_{b,m} \quad \text{eq.14}$$

Where:

- $TBP_{i,b,m}$ is the Theoretical Biomass Potential for country i , within biome b , under management method m .
- $H_{i,b,m}$ is the mass of industrial wood harvested.
- $R_{b,m}$ is the dimensionless residue expansion ratio specific to the biome and harvest method.

In addition to primary harvest residues, secondary process residues (wood residues, wood chips and particles generated during milling and processing) were forecasted. The historical secondary residues data for process residues underwent the identical ETS forecasting methodology to project secondary residue generation up to the target year 2050.

2.3.5. Ecological Retention and Operational Adjustment

To ensure environmental sustainability and account for material recovery limitations, a uniform retention mechanism is applied. The gross theoretical residues are adjusted by a factor of 0.7 (a mean value of 30% retention (Titus et al., 2021)). The retention percent conservatively accounts for the biomass that must remain in situ to maintain soil health, biodiversity, and structural ecosystem integrity, alongside unavoidable logistical losses.

$$NAB_{i,b,m} = TBP_{i,b,m} \times 0.7 \quad \text{eq.15}$$

Where:

$NAB_{i,b,m}$ is the Net Available forestry residue that is available for other usage outside of forests.

2.3.6. Competing Demand and Traditional Usage Allocation

To accurately estimate surplus forestry residue availability, competing traditional household uses of forestry residues, including space heating, water heating, and cooking, were quantified and deducted from the total supply. Data on household traditional energy demand and primary energy

production were obtained from the IMAGE model. First, the share of traditional biomass energy in total primary energy production for 2050 was calculated. Next, total household traditional energy demand in 2050 was aggregated. Multiplying the aggregated household demand by the share of traditional biomass energy yielded the amount of forestry residues utilized for household purposes in 2050. Traditional energy consumption profiles vary significantly depending on regional economic development. Literature indicates that fuelwood accounts for 60% to 95% of the energy consumed in developing nations, while this share drops to 25%–60% in middle-income countries and falls below 5% in developed nations (Eshetu 2024). To accommodate this wide global variance within a unified framework, this study assumes a median global average where 50% of traditional household energy demand is supplied by forestry biomass including residues (Daiglou et al., 2016). Finally, this energy demand was converted into residue mass using the calorific value of wood (19 MJ kg⁻¹; IEA-Bioenergy-Annual-Report, 2024), resulting in an estimate of traditional forestry residue consumption ($R_{traditional}$) expressed in Mg. Because demand data is often aggregated at the regional macro-level, a spatial downscaling approach was utilized. Regional demand totals were distributed to constituent nations based on each country's proportionate share of regional grid cells:

$$D_{country} = D_{region} \times \frac{G_{country}}{G_{region}} \quad \text{eq.16}$$

where D represents the traditional demand and G represents the geographic grid cell footprint.

2.3.7. Net Residue Availability and Scenario Constraints

A comprehensive mass balance was calculated to establish the net available residues prior to scenario constraints. For each country, the projected secondary Process Residues (PR) were added to NAB, and the traditional localized demand was subtracted. The resulting net availability was bound at zero to prevent negative supply projections:

$$R_{net} = NAB + PR - R_{traditional} \quad \text{eq.17}$$

Where R_{net} is the net available forestry residue for industrial utilization. PR is the process residue and $R_{traditional}$ is the amount of residue needed for traditional fuel use in 2050.

2.3.8. Quantification of Competing Industrial Demand

The Energy Transitions Commission (Energy Transitions Commission, 2021) provides deterministic projections for the global biomass requirements necessary to decarbonize hard-to-abate sectors by 2050. To translate these global absolute values into proportionate competitive shares, the industrial demands for aviation and the chemicals and plastics sectors are expressed as minimum and maximum proportional shares of the total sustainable biomass envelope defined in

ETC's "Prudent Scenario". Table 8 and Table 9 outline global biomass availability and requirements for prioritized sectors in 2050.

Table 8. Minimum and maximum global biomass availability by forestry residue.

Type of Feedstock	Global Sustainable Biomass Supply (EJ Year ⁻¹)	
	Min	Max
Forestry Residues	10	20
Total Biomass Available	40	60

Table 9. Projected biomass requirements for prioritized sectors in 2050.

Total Biomass Required for Prioritized Sectors (EJ Year ⁻¹) in 2050	Biomass Required (EJ Year ⁻¹) in 2050	
	Long-haul Aviation	Plastics & Chemicals
54	15	17

2.3.9. Mathematical Derivation of the Net Forestry Residue Feedstock after Competing Demand

To quantify the ultimate net biomass available for biochar production in 2050, the cumulative competitive share (S_{comp}) demanded by the aviation and chemical/plastics sectors must be subtracted from the previously established net available of forestry residue (R_{net}). Because industrial demand trajectories contain inherent long-term uncertainty, the calculation yields a bounded envelope (a minimum and maximum threshold) rather than a single deterministic point. The cumulative competitive share is calculated for both the low-competition and high-competition scenarios (Table 10) by summing the respective sector demands:

$$\text{Low Industrial Competition } (S_{comp,low}) = \text{Aviation}_{min} + \text{Chemical/Plastics}_{min} \quad \text{eq.18}$$

$$\text{High Industrial Competition } (S_{comp,high}) = \text{Aviation}_{max} + \text{Chemicals/Plastics}_{max} \quad \text{eq.19}$$

Table 10. Projected competitive biomass demand shares.

Competing Industrial Sector	Projected Share (%)	
	Min	Max
Aviation	7.0	9.5
Chemicals and Plastics	8.0	10.5

The final Available Biomass Potential (ABP) of forestry residue exclusively for biochar was calculated by discounting the R_{net} by the respective cumulative competitive extraction rates.

Maximum availability of forestry residue for biochar production (low industrial competition):

$$ABP_{max} = R_{net} \times (1 - S_{comp,low}) \quad \text{eq.20}$$

Minimum availability of forestry residue for biochar production (high industrial competition):

$$ABP_{min} = R_{net} \times (1 - S_{comp,hig}) \quad \text{eq.21}$$

By enforcing these subtractive macroeconomic boundaries, the methodology guarantees that the resulting forestry residue volumes reserved for biochar are economically viable and systematically de-risked against the aggressive forestry residue procurement strategies of the aviation and petrochemical sectors.

3.RESULTS

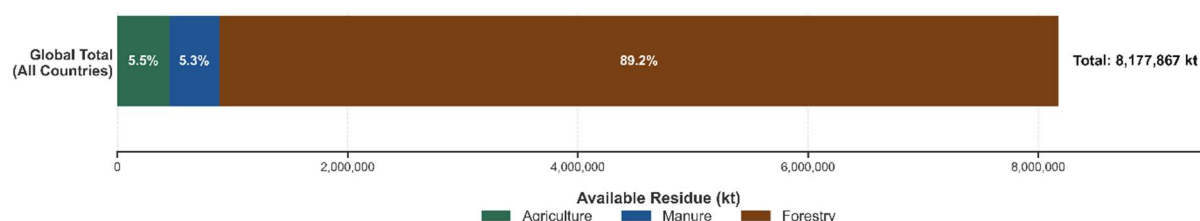
This chapter presents the projected country-level availability of biomass residues for the biochar pathway in 2050. The results are reported for three feedstock sectors: agricultural cereal residues, livestock manure, and forestry residues. The term “available feedstock” refers to residue remaining after the constraints applied in the methodology, including existing uses, sustainability-related retention, and competing industrial demand where relevant. It should not automatically be interpreted as produced biochar mass. Estimated biochar production is reported separately only where feedstock-specific conversion factors are applied. All spatial distribution maps are presented on a logarithmic scale to enhance the visual distinction between countries; however, the reported values represent absolute quantities. Unless otherwise specified, all absolute quantities presented in maps, figures, and tables throughout this chapter are reported in kilo tons (kt) for all feedstock categories. Furthermore, the projected population data for 2050 used in the per-capita maps were sourced from the United Nations Population Division. This chapter is structured around four key questions: (i) how available residues are distributed spatially, (ii) how theoretical generation changes after sustainability and competing-use constraints, (iii) which feedstock sector contributes most to constrained availability, and (iv) which countries have the largest potential for biochar production after feedstock conversion.

3.1. Global residue availability by feedstock type

Across the three sectors, the projected available feedstock in 2050 is strongly dominated by forestry residues. The total available residue pool is 8,177,867 kt. Forestry residues account for 7,293,016 kt or 89.2% of the total. Agricultural residues contribute with 452,353 kt or 5.5% of the total while livestock manure contributes with 432,498 kt, equivalent to 5.3% (Table 11). These results highlight the fact that the largest theoretical biological resource does not necessarily mean the largest available resource. Livestock manure and agricultural residues are constrained by soil retention, bedding, animal feeding, nutrient cycling, field practices et cetera. Forestry residues remain the largest feedstock stream after the implemented constraints because a considerable share is generated through harvesting and processing systems that are more spatially concentrated than manure or dispersed crop residues.

Table 11. Biomass feedstock availability and sectoral distribution.

Feedstock Sector	Feedstock Availability (kt)	Feedstock Share (%)
Forestry residue	7,293,016	89.2
Agricultural residues	452,353	5.5
Livestock manure	432,498	5.3
Total	8,177,867	100

**Figure 1.** Global distribution of available biomass residue by source sector.

3.2. Theoretical generation versus constrained availability

The comparison between theoretical generation and available feedstock is the central result of the study. Manure has the largest theoretical generation at 20,999,355 kt, but only 432, 498 kt remains available after the management and loss rates discounted/applied in the model. This corresponds to an available fraction of 2.1%. Forestry residues have a theoretical potential of 11,840,246 kt of which 7,293,016 kt remains available, corresponding to 61.6%. Also, for agricultural residues the theoretical potential is 3,695,454 kt and only 452,353 kt (12.2%) is available for biochar production (Table 12 and see figure 1, 2, 3 in Appendix). These results highlight the need to not treat theoretical availability as sustainable feedstock supply. Agricultural residues are needed for soil protection, animal feeding and bedding as well as other local uses. Manure on the other hand, is often left on pasture, returned to soil, or constrained by management and recovery limits. Forestry residues are as well constrained by ecological retention, traditional fuel uses as well as competing industrial demand, but the available fraction remains higher than for the two other sectors under the assumptions implemented in this study.

Table 12. Theoretical VS. available biomass by feedstock type.

Feedstock type	Theoretical biomass (kt)	Available feedstock (kt)	Available fraction (%)	Unavailable fraction (%)
Forestry residues	11,840,246	7,293,016	61.6	38.4
Agriculture residues	3,695,454	452,353	12.2	87.8
Livestock manure	20,999,355	432,498	2.1	97.9

3.3. Sector-Specific Spatial Patterns of Feedstock Availability

3.3.1 Agricultural Residue

Agricultural residue availability is concentrated in a small group of major cereal-producing countries. China has the largest available agricultural residue potential, with 156,560 kt in 2050, followed by the United States with 66,599 kt. Indonesia, Brazil, and Vietnam follow with 19,131 kt, 16,474 kt, and 15,174 kt, respectively (Figure 2). Together, these five countries account for approximately 60% (273,938 kt) of the global available agricultural residue pool. The available agricultural residue pool is dominated by maize straw, rice straw, and wheat straw, which together account for 83.3% of available agricultural residues (Figure 3). This pattern reflects the importance of maize-based systems in countries such as the United States and Brazil, and rice-based systems in several Asian countries. Per-capita results identify different countries, including Hungary, Moldova, Ukraine, Croatia, and Latvia, because this indicator emphasizes residue availability relative to population rather than total volume (Figure 4).

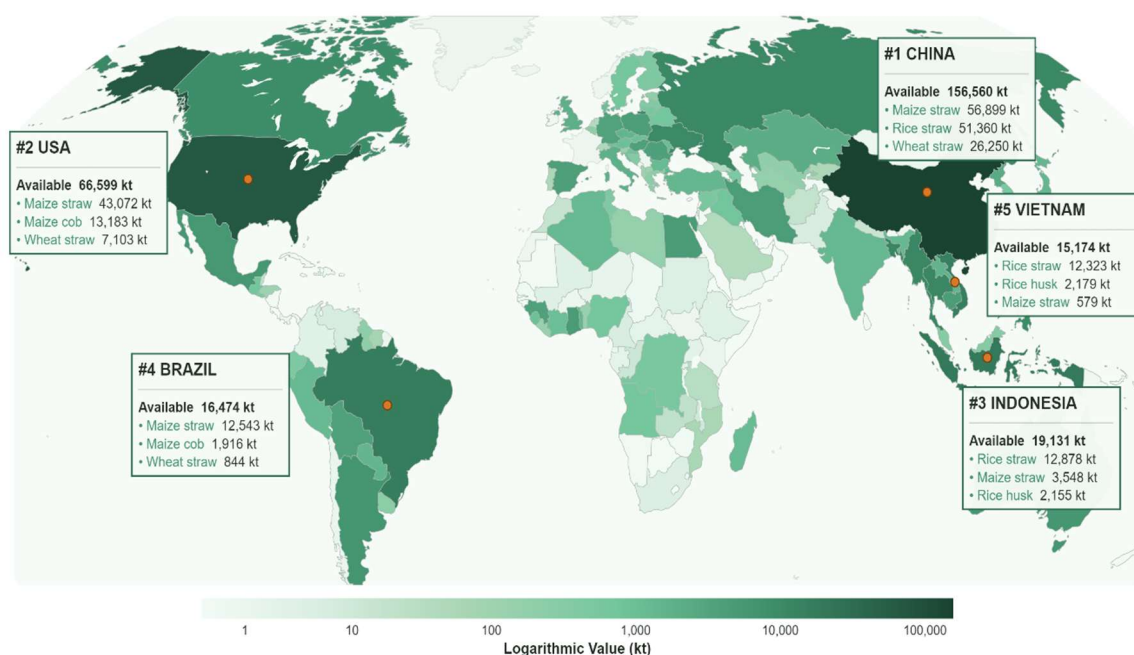


Figure 2. Global spatial distribution of available agricultural residue and top five producing nations.

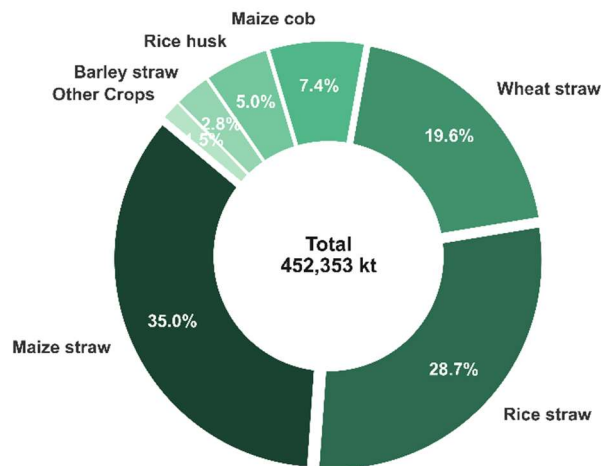


Figure 3. Quantitative composition of available agricultural residue by source crop.

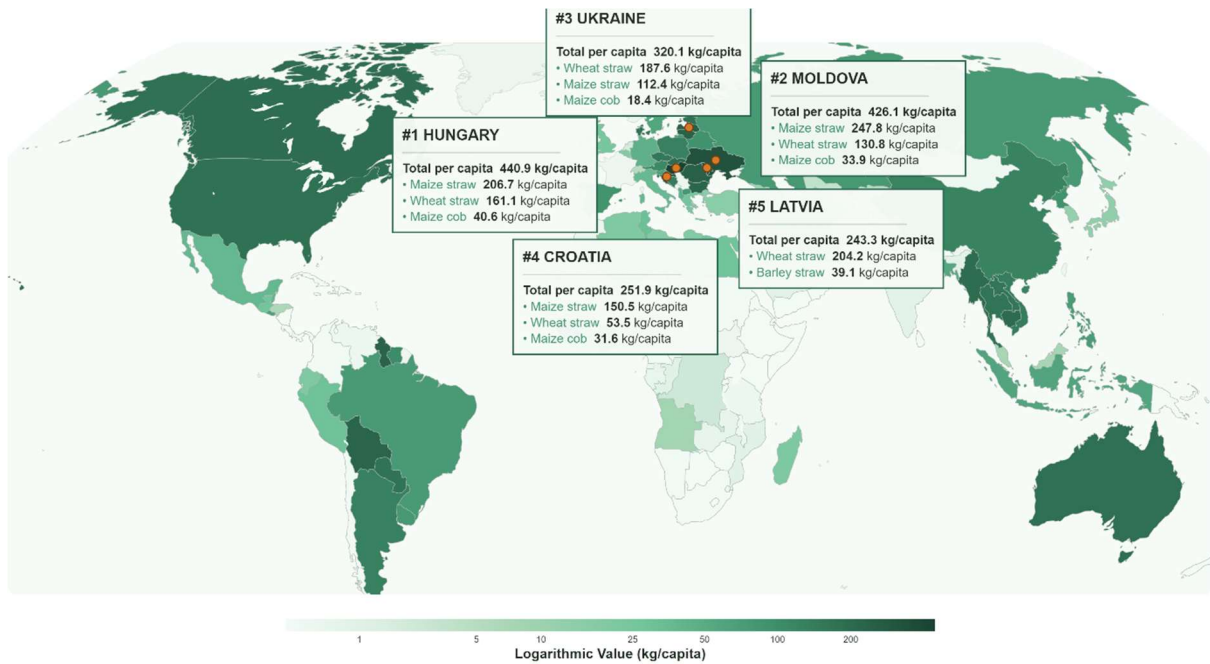


Figure 4. Global spatial distribution of per capita available agricultural residue and top five producing nations.

3.3.2 Livestock Manure

Available manure feedstock is also concentrated in large livestock-producing countries, but the available fraction is much lower than forestry residues. China has the largest available manure feedstock, with 108,854 kt in 2050. India follows with 48,146 kt, the United States with 35,146 kt, Brazil with 16,769 kt, and Russia with 16,203 kt. These five countries together account for approximately 52% of global available manure feedstock (Figure 5).

The dominant livestock categories are non-dairy cattle, chickens, and swine, which together represent 69.4% of available manure. Including dairy cattle increases the combined share to 86.5% (Figure 6). The per-capita ranking shifts toward countries where livestock production is large relative to population, such as Ireland, Mongolia, Belarus, Denmark, and New Zealand. These per-capita results should be interpreted cautiously because local collection systems, nutrient-recycling needs, and manure-management regulations determine whether manure can be diverted to biochar pathways (Figure 7).

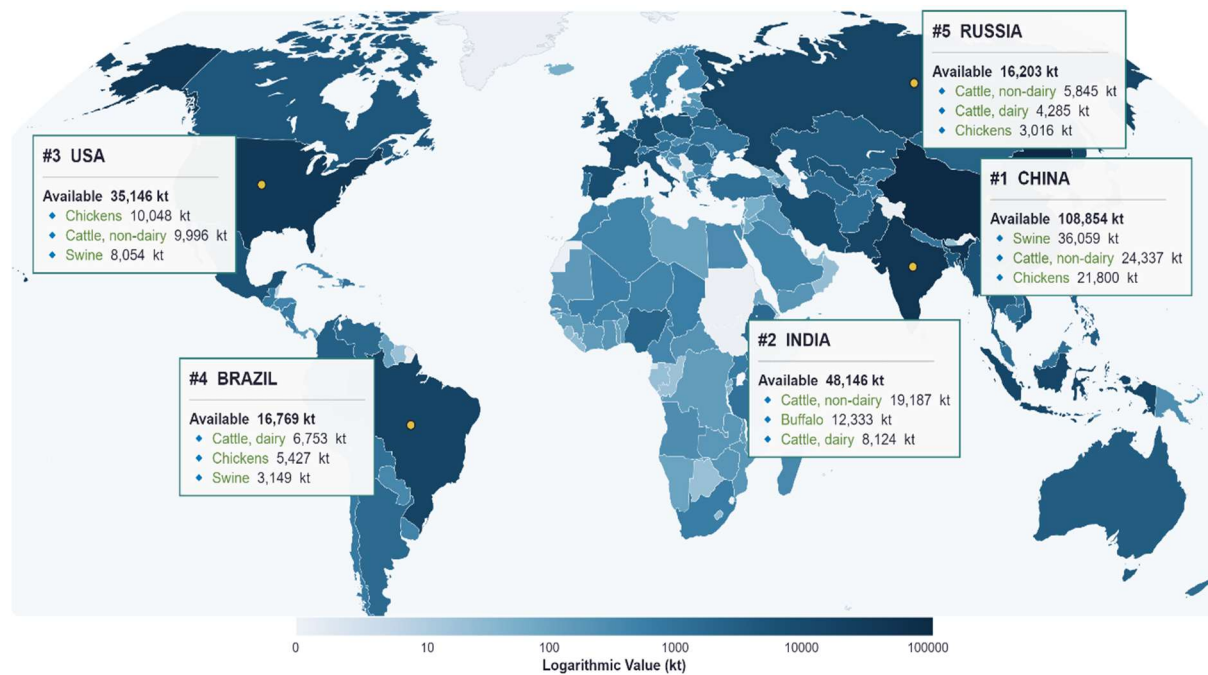


Figure 5. Global spatial distribution of available manure and top five producing nations.

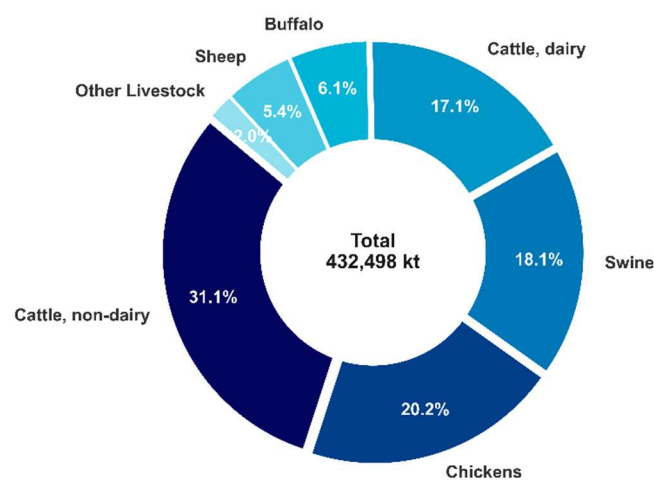


Figure 6. Quantitative composition of available manure by source livestock.

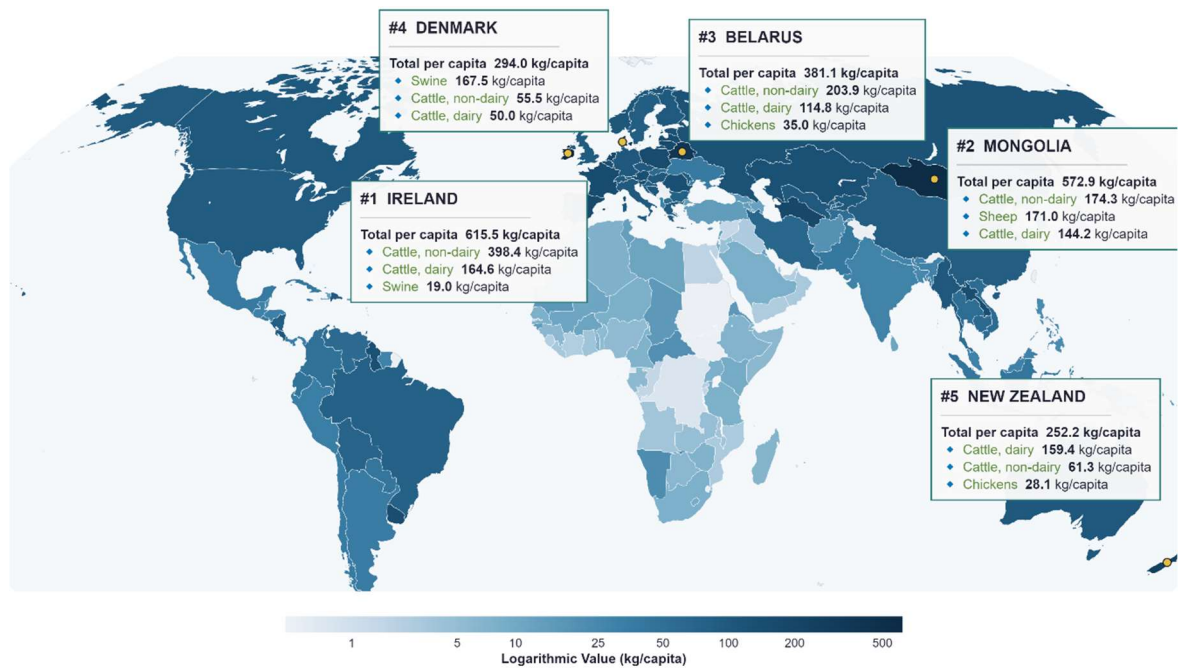


Figure 7. Global spatial distribution of per capita available manure and top five producing nations.

3.3.3 Forestry residues

Forestry residues dominate the constrained feedstock results. In absolute terms, China has the largest available forestry residue potential, with 1,186,642 kt, closely followed by the United States with 1,152,171 kt and India with 980,166 kt. Brazil and Russia complete the top five, with 486,616 kt and 431,310 kt, respectively. These countries dominate because of their large land areas, forest resources, and industrial wood-production systems (Figure 8).

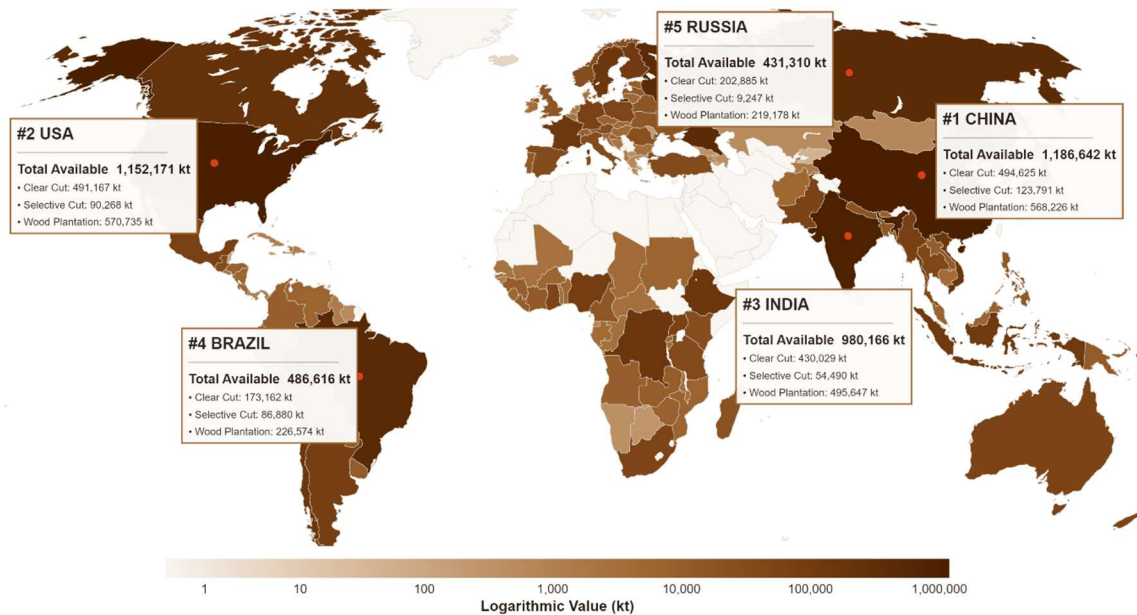


Figure 8. Global spatial distribution of available forestry residue and top five producing nations.

Per-capita forestry availability shifts the ranking toward sparsely populated and highly forested countries, including Finland, Sweden, Bhutan, Latvia, and New Zealand (Figure 9). This contrast between absolute and per-capita rankings is important. Absolute availability identifies potential industrial-scale feedstock hubs, whereas per-capita availability identifies countries with comparatively high residue availability relative to population size. Wood plantations constitute the dominant forest management method, accounting for 48.7% of the available forestry residues. This is followed by clear-cut and selective-cut management practices, which contribute 41.4% and 9.9% of the available forestry residues, respectively (Figure 10).

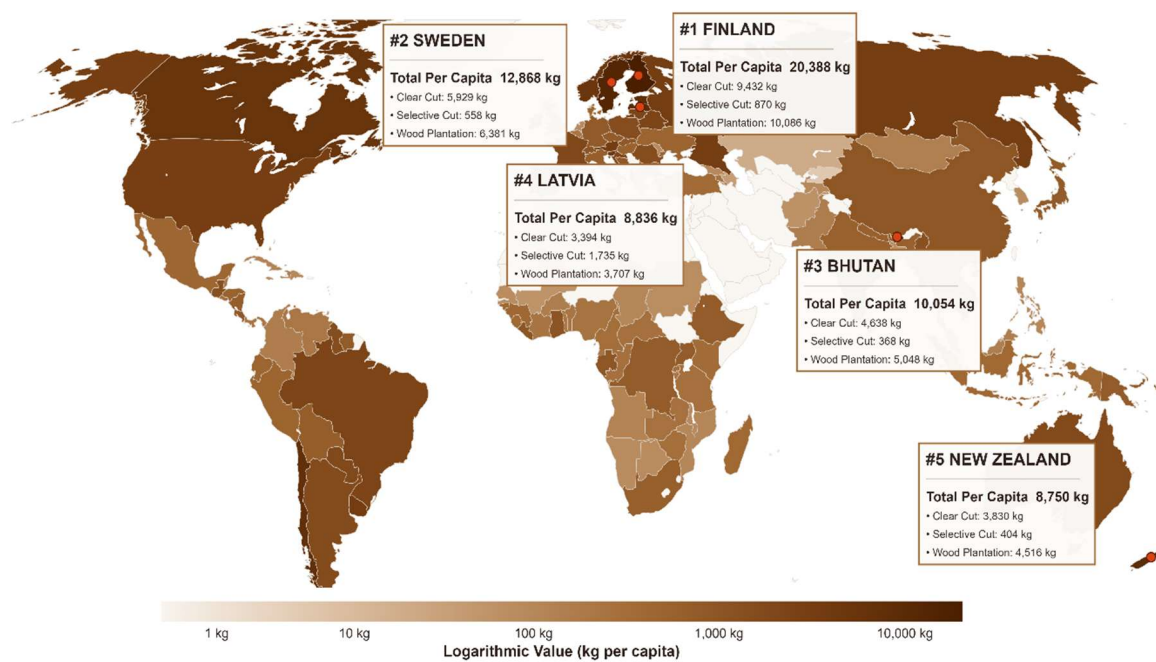


Figure 9. Global spatial distribution of per capita available forestry residue and top five producing nations.

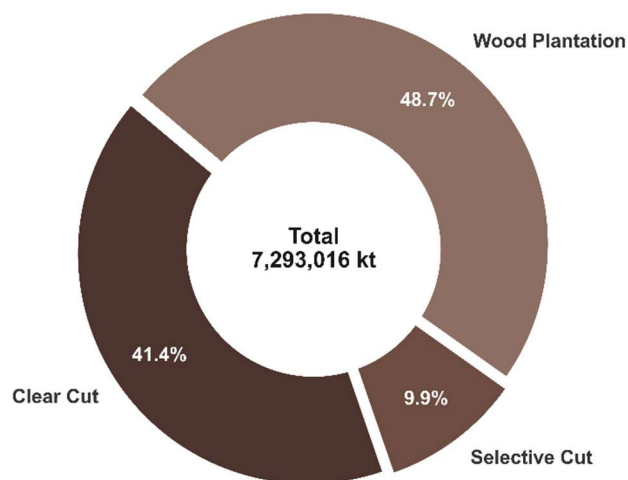


Figure 10. Quantitative composition of available forestry residue by source management method.

Table 13 provides an overview of global feedstock availability across the Agriculture, Manure, and Forestry sectors. China, the United States, and Brazil consistently rank among the top countries for available feedstock across all three categories. The data highlights that while agriculture relies heavily on cereal straws (maize, rice, and wheat) and manure offers large theoretical production from livestock, it is the forestry sector that provides the largest available stream of feedstock due to its highly centralized residues from wood plantations and clear-cuts.

Table 13. Sectoral analysis of global feedstock availability and source constraints.

Sector	Top countries by available feedstock	Main internal contributors	Interpretation
Agriculture	China; United States; Indonesia; Brazil; Vietnam	Maize straw; rice straw; wheat straw	Concentrating on major cereal-producing systems; per-capita leaders differ from absolute leaders.
Manure	China; India; United States; Brazil; Russia	Non-dairy cattle; chickens; swine; dairy cattle	Large theoretical production, but management and nutrient-cycling constraints leave only a small available fraction.
Forestry	China; United States; India; Brazil; Russia	Wood plantation, clear-cut, and selective-cut residues	Largest available stream because residues are more centralized than crop residues or pasture manure.

3.4. Integrated country-level distribution of available feedstock

When all three sectors are combined, total available feedstock concentrated in a small number of countries. China has the largest total, with 1,452,056 kt, followed by the United States with 1,253,916 kt and India with 1,029,625 kt. Brazil and Russia follow with 519,859 kt and 458,124 kt, respectively. Canada, Vietnam, Ethiopia, Indonesia, and the Democratic Republic of the Congo complete the top ten.

The top-country ranking is driven by forestry residues. In China, forestry accounts for 1,186,642 kt of the total, compared with 156,560 kt from agriculture and 108,854 kt from manure. The same pattern is observed in the United States, where forestry contributes 1,152,171 kt, while agriculture and manure contribute 66,599 kt and 35,146 kt, respectively. In India, forestry contributes 980,166 kt, manure contributes 48,146 kt, and agriculture contributes 1,313 kt. The integrated ranking therefore shows that forestry residues dominate not only globally, but also within most of the largest national feedstock pools.

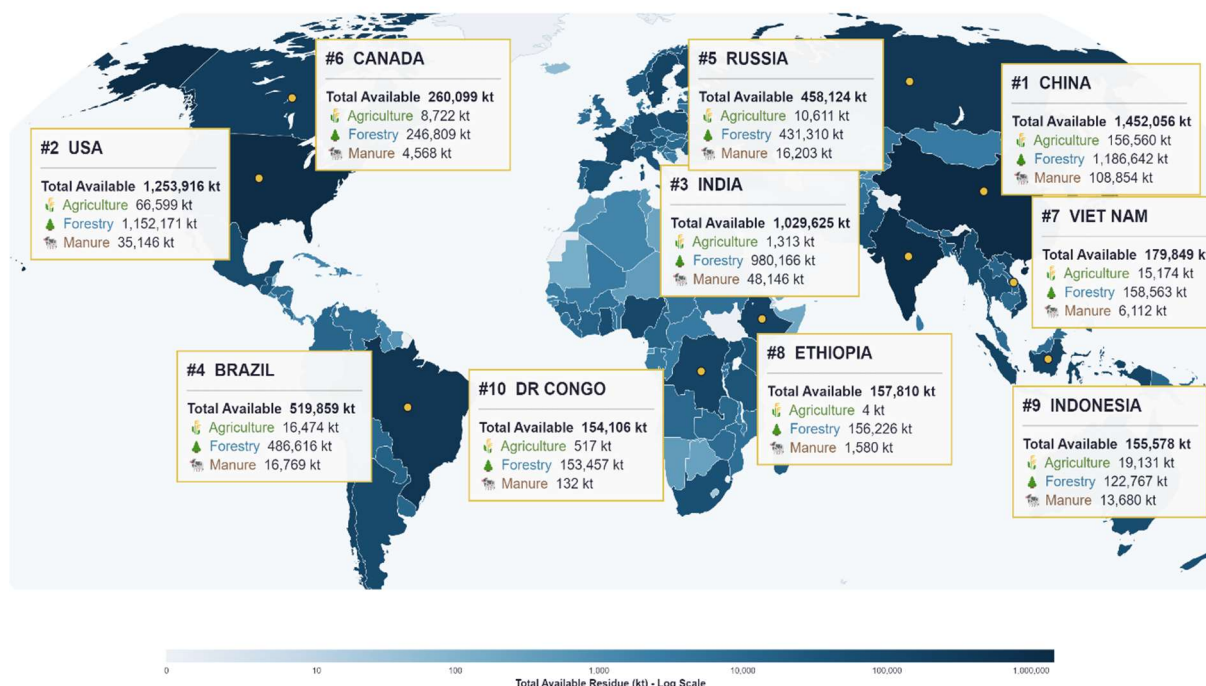


Figure 11. Available residue based on feedstock type: top 10 countries (2050).

3.5. Estimated Potential for Biochar Production

This section discusses the estimated potential for biochar production separately from feedstock availability. The results above report on available residue feedstock mass rather than produced biochar mass. The analysis estimates biochar production potential only after applying feedstock-specific conversion factors (see Table 7 in Appendix). After applying these conversion factors, China has the highest estimated biochar production potential, at 485,135 kt. The United States follows with 399,263 kt and India with 333,698 kt. Brazil and Russia complete the top five, with 166,572 kt and 147,389 kt, respectively. The same forestry dominance observed in feedstock availability also appears in the biochar-output ranking, because forestry residues provide the largest available mass and favorable conversion characteristics compared with wetter feedstocks.

This result represents the technical biochar mass potential based on the modelled feedstock and should not be interpreted as net CO₂ removal. A full CDR estimate would require additional assumptions about biochar carbon content, stability or permanence, transport and processing emissions, energy co-product accounting, and final use or storage conditions.



Figure 12. Biochar production based on feedstock type: top 10 countries (2050).

4.DISCUSSION

The results of this study confirm one of the central arguments in the biomass and biochar literature: theoretical residue generation is a poor indicator of practical feedstock availability. Across the three sectors analyzed, the global theoretical biomass base is exceptionally large, but most of this biomass cannot be assumed to be freely available for biochar production. Livestock manure has the largest theoretical generation, but only a small fraction remains available after manure-management, soil-application, and loss constraints are applied. Agricultural residues are also strongly reduced once soil retention, livestock feed, and bedding, burning, and competing industrial demand are considered. Forestry residues retain a much larger available fraction, but they are still constrained by ecological retention, traditional fuel use, and competition from other bioeconomy sectors. This confirms the need to distinguish clearly between theoretical biomass, sustainably available feedstock, estimated biochar output, and net carbon dioxide removal.

This distinction is consistent with the findings of Lefebvre et al., (2023) and Karan et al., (2023), both of whom emphasize that biochar potential is extremely sensitive to sustainability constraints and feedstock availability assumptions. Lefebvre et al., (2023) show that global biochar mitigation potential depends not only on the quantity of residues generated, but also on collection factors, pyrolysis yields, and permanence assumptions. Similarly, Karan et al., (2023) demonstrate that the technical potential from crop residues decreases substantially once sustainable harvesting limits and competing uses are included. The present study reaches a similar conclusion from a broader feedstock perspective: **the limiting factor is not only biological production, but the fraction of that production that can be diverted without compromising existing ecological, agronomic, or economic functions.** In this sense, the results support the wider literature warning that residue-based biochar assessments must not treat all generated biomass as available biomass.

The strong reduction in available agricultural residues is particularly important. Although crop residues are one of the most frequently discussed biochar feedstocks, this study shows that their available share is small after accounting for existing residue-use pathways. This result is consistent with the literature showing that crop residues have important soil and livestock functions (Luo et al., 2023; Mouratiadou et al., 2020). Returning residues to soil contributes to erosion control, moisture retention, organic carbon maintenance, and nutrient cycling, while residues are also used for animal feed and bedding in many agricultural systems (Turmel et al., 2015; Lal, 2005). Therefore, the low agricultural availability found here should not be interpreted as a weakness of crop residues as a feedstock, **but rather as evidence that their sustainable mobilization requires careful local assessment.** Large cereal-producing countries such as China, the United

States, Indonesia, Brazil, and Vietnam remain important potential hubs, but the amount that can be diverted to biochar is much smaller than the theoretical residue pool.

The manure results show an even sharper contrast between theoretical generation and available feedstock. This finding is consistent with Sileshi et al., (2025), who highlight that livestock manure is globally abundant but difficult to assess and mobilize uniformly because of management systems, nutrient-recycling needs, and data quality differ strongly between countries. Manure is not simply an unused waste stream, it is often deposited on pasture, returned to soil, or already managed within existing agricultural systems. The low available fraction estimated in this study therefore reflects not only a technical limitation but also the agronomic role of manure as an organic fertilizer. This is important for interpreting manure-based biochar pathways. **Manure may offer strong local opportunities where collection systems already exist, especially in intensive livestock regions, but its global scalable potential is more constrained than its theoretical mass would suggest.**

Forestry residues dominate the available feedstock pool in this study, accounting for the largest share of constrained biomass availability. This result differs from some bioenergy studies, such as Mensah et al., (2025) where crop residues dominate the global sustainable bioenergy potential. The difference is not necessarily a contradiction. Bioenergy studies often compare feedstocks using energy potential and may include different collection assumptions, conversion efficiencies, and feedstock categories. In contrast, this thesis evaluates residue availability for biochar pathways after applying sector-specific constraints and competing-use deductions. Under these assumptions, forestry residues remain more available because they are often generated through more centralized harvesting and processing systems than dispersed crop residues or pasture-based manure. However, this should not be interpreted as evidence that forestry residues are unrestricted. Their use still requires ecological retention to protect soil fertility, biodiversity, and forest regeneration, as well as safeguards against overextraction and indirect pressure on forest systems. The dominance of forestry also explains the country-level pattern observed in the results. The largest total feedstock potentials are concentrated in China, the United States, India, Brazil, and Russia, and this ranking is driven by forestry residues rather than by agriculture or manure alone. This aligns with the broader literature reviewed in this thesis, which shows that biochar and biomass potentials are spatially uneven and often concentrated in countries with large agricultural or forestry sectors. Lefebvre et al., (2023) similarly identify major countries such as China, the United States, Brazil, and India as important contributors to absolute biochar mitigation potential. **The present study extends this perspective by showing that, when agriculture, manure, and forestry are evaluated together under a harmonized 2050 framework, forestry residues**

strongly shape the global distribution of available feedstock and estimated biochar production potential.

At the same time, the results should not be interpreted only through absolute national totals. The contrast between absolute and per-capita availability is important for deployment planning. Absolute availability identifies countries where large-scale industrial biochar systems may have the greatest feedstock base. Per-capita availability, by contrast, highlights countries where biomass surplus is large relative to population size. **These two indicators answer different policy questions. A country with extremely high absolute availability may be suitable for centralized production and international biomass or biochar markets, while a smaller country with high per-capita availability may have strong domestic potential but limited global scale.** This distinction is important because biochar deployment depends not only on feedstock mass, but also on infrastructure, transport distances, policy incentives, soil demand, and the location of pyrolysis facilities.

The results also contribute to the methodological gap identified by Jacobson and Jones, (2025) who emphasize that biomass assessments are often difficult to compare because of inconsistent terminology, units, categories, and sustainability assumptions. This thesis addresses part of that challenge by applying a harmonized country-level framework across agriculture, manure, and forestry residues. It also responds to the research gap identified in this thesis by projecting feedstock availability to 2050 rather than relying only on current or near-term residue estimates. **However, the results should still be interpreted as model-based estimates rather than definitive resource quantities.** The forecasts depend on historical data quality, time-series extrapolation, parameter assumptions, and the availability of country-level information. For some countries and sectors, FAOSTAT values may include estimated or imputed data, and the uncertainty associated with these values is not fully propagated through the results.

Finally, the estimated biochar production potential should not be equated with net carbon dioxide removal. The conversion from available feedstock to biochar mass is an important intermediate result, but net CDR would require additional modelling of feedstock carbon content, pyrolysis conditions, biochar stability, soil residence time, transport emissions, processing emissions, avoided emissions, and end-use pathways. This distinction is important considering the broader CDR literature. Ampah et al., (2024) emphasize that CDR options must complement, not replace, emissions reductions, and that deployment choices involve land, water, food, and policy trade-offs. **Therefore, the results of this thesis should be interpreted as a global feedstock-availability and technical biochar-production assessment, not as a complete life-cycle**

carbon-removal estimate. The main contribution is to identify where sustainable residue feedstocks may be available by 2050 and how strongly that availability changes once ecological, agronomic, logistical, and industrial constraints are included.

5.CONCLUSIONS

This thesis quantified the projected country-level availability of sustainable biomass residues for biochar pathways in 2050, focusing on three major feedstock sectors: agricultural cereal residues, livestock manure, and forestry residues. The study was motivated by the need to distinguish between the large theoretical biomass resource base often reported in global assessments and the smaller fraction that can realistically be mobilized after ecological, agronomic, logistical, and competing-use constraints are considered. By combining historical production and livestock data, time-series forecasting, residue conversion parameters, management constraints, and industrial competition assumptions, the analysis provides a harmonized prospective assessment of feedstock availability for biochar production at global-national resolution.

The first major conclusion is that theoretical biomass generation overestimates the amount of feedstock available for biochar production. Across all three sectors, the results show that biomass residues already perform crucial functions within existing ecological and economic systems. Agricultural residues contribute to soil protection, nutrient cycling, animal feed and bedding, and other local uses. Manure is frequently left on pasture, applied to soil, or otherwise managed within agricultural systems. Forestry residues are constrained by ecological retention requirements, traditional fuel use, and competing demand from other bioeconomy sectors. Therefore, the central finding of this work is not simply that large volumes of residues exist globally, but that only a constrained share of this biomass can be considered available for diversion into biochar pathways.

The second major conclusion is that forestry residues dominate the global available feedstock pool under the assumptions applied in this study. In 2050, total available feedstock across the three sectors is estimated at 8,177,867 kt. Forestry residues account for 7,293,016 kt, or 89.2% of this total, while agricultural residues contribute 452,353 kt, equivalent to 5.5%, and livestock manure contributes 432,498 kt, or 5.3%. This result does not imply that forestry residues are unconstrained or automatically sustainable to extract. Rather, it indicates that forestry residues remain more available than crop residues and livestock manure after the sustainability and competing-use filters used in this study are applied. Their dominance is partly explained by the fact that many forestry residues are generated through relatively centralized harvesting and processing systems, whereas agricultural residues and livestock manure are more dispersed and more strongly embedded in soil and livestock systems.

The comparison between theoretical generation and constrained availability further demonstrates the importance of applying sector-specific constraints. Forestry residues have

a theoretical potential of 11,840,246 kt, of which 7,293,016 kt remains available, corresponding to 61.6%. Agricultural residues have a theoretical potential of 3,695,454 kt, of which 452,353 kt remains available, corresponding to 12.2%. Livestock manure has the largest theoretical biomass generation, estimated at 20,999,355 kt, but only 432,498 kt remains available after management and loss constraints, corresponding to 2.1%. These results show that the largest gross biomass stream is not necessarily the most useful or accessible stream for biochar deployment. Availability depends on management context, collection feasibility, ecological retention needs, and existing demand.

At the country level, available feedstock is concentrated in a relatively small number of large biomass-producing countries. China, the United States, India, Brazil, and Russia form the leading group in terms of total available feedstock. This ranking is driven by forestry residues, although agriculture and manure also contribute to specific national contexts. The same geographic concentration appears in the estimated biochar production potential after feedstock-specific conversion factors are applied. China shows the largest estimated biochar production potential, followed by the United States, India, Brazil, and Russia. However, these estimates should be interpreted as technical biochar mass potential, not as net carbon dioxide removal. Translating biochar mass into durable CDR would require additional assumptions on carbon content, pyrolysis conditions, stability, soil residence time, transport emissions, processing emissions, and end use.

The findings are consistent with the broader literature showing that residue-based biochar potential is extremely sensitive to sustainability constraints, residue retention assumptions, and competing uses. Previous studies have emphasized that biochar can contribute to climate mitigation, but that its realistic potential depends on the availability of sustainable biomass residues rather than on theoretical biomass generation alone. This thesis supports that conclusion and extends it by applying a harmonized 2050 country-level framework across agriculture, manure, and forestry residues. The results also reinforce the need to treat biomass residues as context-dependent resources, not as universally available waste streams. Residues often already provide valuable services, and their diversion to biochar must be assessed against local soil, livestock, energy, and ecosystem needs.

From a deployment perspective, the results suggest that biochar strategies should be spatially differentiated. Countries with large absolute feedstock availability may be better suited for industrial-scale biochar production, centralized pyrolysis infrastructure, and integration with national CDR planning. In contrast, countries with high per-capita availability may have smaller total volumes but stronger local surplus potential relative to population size. These countries may

be suitable for decentralized or regionally targeted biochar systems, particularly where local agricultural soils can benefit from biochar application. Therefore, both absolute and relative indicators are needed: absolute availability identifies large-scale supply hubs, while per-capita availability helps reveal domestic surplus and potential local relevance.

Limitations need to be acknowledged. The projections are based on historical trends extended to 2050 and therefore do not fully capture future climate-change feedback, including drought, shifting crop productivity, pest pressures, forest fires, land-use change, or changes in livestock systems. Sustainable Aviation Fuel (SAF) and chemicals/plastics competition is applied as a fixed global share. This ignores country-level demand, logistics, trade, policy, infrastructure, and feedstock type, and it is a scenario simplification for lack of better data. The analysis also depends on the quality and consistency of FAOSTAT and other global datasets, which may include estimated or incomplete values for some countries. In addition, several conversion and management parameters are applied as fixed assumptions, even though real-world values may vary by technology, region, and management system.

Future research should therefore focus on improving uncertainty propagation, incorporating climate-change impacts on biomass production, and refining country-specific collection and sustainability constraints. More detailed modelling of transport distances, pyrolysis facility location, economic feasibility, and policy conditions would improve the transition from feedstock availability assessment to deployment planning. A full carbon dioxide removal assessment should also integrate life-cycle emissions, biochar stability, carbon permanence, avoided emissions, and end-use impacts. Such extensions would allow the feedstock availability estimates produced here to be translated into more complete estimates of net CDR potential.

Overall, this thesis demonstrates that sustainable biomass residues could provide a substantial feedstock base for future biochar production, but that this potential is unevenly distributed and much smaller than theoretical biomass generation suggests. Forestry residues dominate the constrained global feedstock pool, while agricultural residues and manure remain important but more limited by soil, livestock, and management constraints. The main contribution of this work is therefore a harmonized, country-level, forward-looking assessment that clarifies where sustainable feedstock may be available in 2050 and highlights the importance of distinguishing theoretical biomass, available feedstock, estimated biochar production, and net carbon dioxide removal. This distinction is essential for realistic biochar-based CDR planning.

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