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Availability of solid biomass from residues in developing countries for renewable energy and negative emissions

Environmental and social compatibility, as well as competing uses / global quantitative framework

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Foreword

Biomass is important when it comes to climate change mitigation because plants can absorb CO_2 from the air and use it to build energy-rich plant structures without the need for fossil energies. Electricity or fuels can then be produced from biomass without any CO_2 emissions. Biochar produced from biomass, in turn, can permanently sequester carbon in the soil.

However, biomass has also drawn criticism as an energy source because growing it can destroy biodiversity or threaten food security. In Indonesia, for example, many hectares of rainforest have been cleared to create land for growing oil palms as a source of fuel. In other places, farmers grow rapeseed for fuel rather than grain for food on their fields if this is more profitable.

Unlike these energy crops, biomass from residues is a by-product of food or timber production and may, in some cases, pose no environmental or ethical concerns. As an organisation committed to combating climate change, we therefore ask ourselves two questions: what are the characteristics of “genuine” biomass from residues that are sustainable and thus both environmentally and socially compatible? And how much of this genuine biomass is available for climate applications?

The existing research on the quality and globally available quantities of biomass from residues is insufficient. Only a few analyses apply criteria for environmental and social compatibility, and even then, these are often not completely transparent. Furthermore, there are hardly any studies on the potential of biomass from residues in developing and emerging economies that are relevant to our work as a climate organisation focusing on justice between the Global North and South. Previous studies have either estimated the total global potential or limited their scope to specific regions like the European Union. For this reason, we have conducted our own comprehensive analysis of the environmentally and socially compatible potential of biomass from residues in the Global South. This analysis is based on our own evaluation of databases and literature, as well as questionnaires sent to experts in the various regions.

Our partner in this endeavour, the Institut für Energie- und Umweltforschung Heidelberg (ifeu), provided us with valuable expertise, particularly in establishing criteria for environmental and social compatibility and in assessing specific cases of biomass. We would also like to thank the PtX Lab Lausitz for reviewing this study and the Deutsche Biomasseforschungszentrum (DBFZ) for their feedback. Dr Carsten Loose also gave us valuable suggestions and insights thanks to his many years of work for the German Advisory Council on Global Change (WBGU). Our sister company, Solarbelt gGmbH, contributed practical experience in biomass-to-liquid production to the study. We would like to express our special thanks to the agricultural experts who, through questionnaires and interviews, provided information on the environmental and social compatibility and availability of various types of biomass from residues in the Global South. Finally, we would like to thank Joram Schwartzmann, who proofread the study and was responsible for the layout.

We hope you find our study interesting and we look forward to receiving suggestions for projects that harness the considerable potential of biomass from residues for climate change mitigation.

Dr Wolfdietrich Peiker

Dr Dietrich Brockhagen

Abstract

Solid biomass from residues is suitable for various climate applications necessary to achieve the 1.5-degree target. It can be used to produce CO_2-neutral electricity through direct combustion or gasification, CO_2-neutral hydrocarbons such as kerosene through gasification and biochar through pyrolysis, which generates negative emissions. Compared to energy crops, biomass from residues are suitable for climate applications as they essentially do not compete with food production. This raises the question of the quantity of biomass residues actually available for climate change mitigation. No quantitative analysis incorporating comprehensive criteria for environmental and social compatibility has been conducted to date. This study bridges that gap. It combines a top-down with a bottom-up approach.

We focus on dry residues such as crop residues or wood chips, as well as sewage sludge, because the data available to estimate the potential quantity is significantly better here than for wet residues such as food waste. Furthermore, we limit the study to developing and emerging economies, as this is the focus of atmosfair's work as an international organisation dedicated to tackling climate change.

In the top-down approach, the study derives a set of criteria from the United Nations Sustainable Development Goals, which are applied to solid biomass from residues. In the bottom-up approach, we carry out a quantitative estimate using our own interviews and external studies, creating a comprehensive quantitative framework for a number of countries and types of residues.

Based on a global total of 7 billion tonnes of solid biomass per year, or 3.5 billion tonnes in developing and emerging countries, our analysis estimates a total of 420 million tonnes of environmentally and socially compatible and available biomass from residues.

This could be used to generate 645 terawatt hours of electricity, 125 million tonnes of biochar or 60 million tonnes of synthetic hydrocarbons annually, from which 40 million tonnes of kerosene could be produced. With all three climate applications, the biomass would not only help to reduce CO_2 emissions, it could also boost economic and social development in the Global South, where people are hardest hit by the impacts of climate change.

I. Summary

I. Goal of the study

This study looks at how much environmentally and socially compatible solid biomass from residues is available in the Global South for climate applications. Solid residues are suitable for use in the production of:

- CO_2-neutral electricity and heat by means of direct combustion or gasification in power stations
- CO_2-neutral hydrocarbons such as kerosene by means of gasification and then Fischer-Tropsch synthesis (biomass-to-X, BtX)
- Biochar by means of pyrolysis

This study focuses on these three applications. While the first two applications prevent fossil CO_2 emissions, biochar, as a soil improver in fields, actually generates negative emissions.

Scope and "genuine" biomass from residues

Biomass contains energy which, when used, releases only as much CO_2 as the plants absorbed from the atmosphere and stored in their structures during growth. The use of biomass is therefore essentially CO_2-neutral. However, energy crops containing starch, sugar and oil, such as sugarcane or oil palms, have drawn criticism because growing them competes for land with food crops. As a result, this study focuses on genuine biomass from residues generated by the agriculture, forestry or waste sectors, which is currently only combusted or otherwise disposed of, goes unused or is even harmful to the climate (such as crop residues from wet rice cultivation). Specifically, we consider agricultural and wood residues as well as sewage sludge, because the data available to estimate the potential usable quantity is significantly better than for wet residues such as household waste or animal manure. However, these wet residues also presumably offer significant unharnessed energy potential.

In the study, we develop criteria to ensure that, from an environmental and social perspective, the biomass is indeed "genuine" residues with the above-mentioned properties, and apply these criteria to the global primary potential of biomass from residues. The remaining quantities identified this way can then be used for environmentally and socially compatible climate applications. By applying these criteria, we exclude over 90% of biomass from residues because it should either not be removed from the ecosystem – such as cereal residues in arid and semi-arid zones – or because it is already better used elsewhere (e.g. as animal feed, for textiles or in chipboard), or because its use would, for example, jeopardise smallholder structures.

The study focuses on biomass from residues in developing and emerging economies of the Global South, as these countries are particularly vulnerable to climate change and because the use of biomass can give them important impetus for economic and social development. The study concludes that a total of approximately 420 million tonnes of biomass from residues is available annually in countries of the Global South. This could be used to produce 645 terawatt hours of electricity, 125 million tonnes of biochar or 60 million tonnes of hydrocarbons, including 40 million tonnes of kerosene, which could meet 20% of what is needed for global aviation in 2022. A rough estimate of the quantity of wet residues such as food waste and animal manure suggests that 1.25 billion tonnes of this amount could potentially be used. Through biogas fermentation, a further 200 terawatt hours of electrical energy could be generated.

From a development perspective, all three climate applications benefit the local population in developing and emerging economies. If the residues are used in power stations, clean electricity is generated, which is still in short supply in some countries. Biochar not only permanently sequesters carbon in the soil but, when used as a soil improver, increases the fertility of farmland. Biomass-to-liquid kerosene (BtL) can be used in the producing countries themselves. However, it can also generate revenue as a high-value export product.

II. 5-step approach

Figure a shows how we filter the world's solid biomass from residues in several steps to estimate the actual usable potential of biomass:

1. Technical suitability, no energy crops: We start with all solid biomass from residues worldwide that is technically suitable for our three climate applications. These include husks, wood chips or rice straw, but also dried sewage sludge. We consider only waste and no energy crops that could compete with food production.
2. Developing countries only: We focus on countries in the Global South that are hardest hit by climate change and can benefit economically and socially from the use of these residues.
3. Environmental and social compatibility: In this step, we determine the quantity of biomass from residues that complies with the principle of sustainability and is therefore grown under conditions that are both environmentally and socially compatible.
4. No competing use: We determine the quantities of biomass from residues that are not used for any other purpose or are burned and are therefore available for climate applications.
5. Economic potential: It is difficult to calculate the actual amount of residues that can be used economically. We therefore discuss this aspect only in qualitative terms.

III. Determining environmental and social compatibility and availability

Top-down approach:

We use the UN's Sustainable Development Goals (SDGs) to derive principles and criteria for determining which solid biomass from residues is environmentally and socially compatible:

- Principle 1 – Prioritise land for food and biodiversity: The residues must not originate from energy crops that compete with food crops for farmland. Furthermore, areas with high biodiversity, such as rainforests, must be protected.
- Principle 2 – Climate change mitigation and environmental protection Farming methods should not harm the climate, soil, water or air. For this reason, for example, no pesticides or artificial fertilisers should be used.

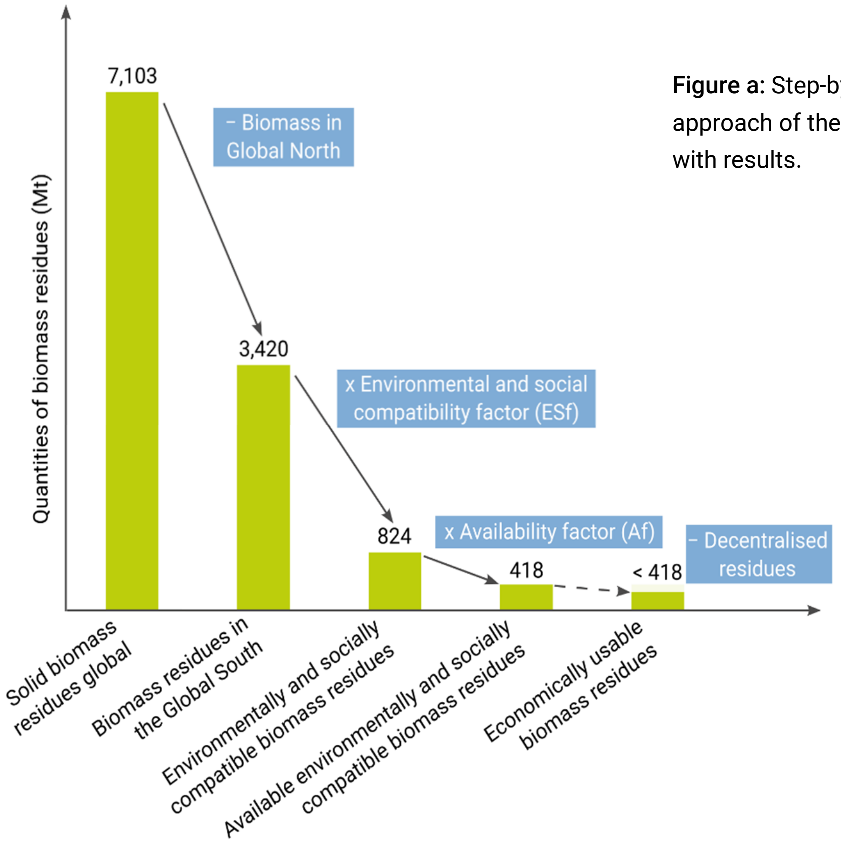

Figure a: Step-by-step approach of the study with results.

- Principle 3 – Protect and promote human rights and smallholder structures Biomass from residues must not originate from production involving exploitation or human rights violations. Furthermore, the positive impact on the income of smallholder farmers should outweigh any negative effects, and no dependencies should arise.
- Principle 4 – Prioritise biomass for food, soil improvement, materials

Table a: Evaluation of various types of biomass based on principles and criteria for environmental and social compatibility (excerpt). The last column does not represent a quantitative arithmetic average of the individual criteria, but rather an overall qualitative rating based on the criteria.

	Principle 1: Prioritise land use for food and biodiversity		Principle 2: Climate change mitigation and environmental protection				Principle 3: Protect and promote human rights and smallholder structures		Principle 4: Prioritise the use of biomass for food, soil improvement, material use and small-scale energy generation			Overall assessment
	Exclude energy crops	Preserve biodiversity	Protect soil	Protect water	Protect the air	Reduce greenhouse gases	Protect human rights and workplace safety	Create development opportunities for smallholders	Prioritise use as animal feed	Prioritise biomass for soil improvement and materials	Prioritise optimal energy use	
Cocoa (pods)	①	②	②	②	①	②	②	②	①	①	②	②
Maize (straw/cob)	③	②	②	②	①	②	①	②	③	②	①	③*
Cassava (stems)	①	①	②	①	①	①	①	①	①	①	②	①
Oil palm (berries/fibres/shells)	③	③	③	②	②	③	③	③	①	②	②	③
...	...	...	...	...	...	...	...	...	...	...	...	...

and small-scale energy generation As it is more environmentally and socially compatible to use biomass as animal feed, fertiliser, building material or fuel for smallholder households, these uses should be prioritised.

Bottom-up approach, qualitative and quantitative

We apply these principles to various types of biomass and initially classify them qualitatively into three categories based on various studies and literature sources (Table a):

- Biomass from residues such as cassava stems, rice straw or sewage sludge that is generally environmentally and socially compatible (①)
- Biomass from residues such as cotton stalks, coffee husks or sawmill by-products that is environmentally and socially compatible depending on circumstances (②)

- Biomass from residues such as oil palm residues that is mostly not environmentally and socially compatible This also includes maize and soya residues, as we consider only a small percentage of these to be suitable for human consumption (③).

This qualitative assessment provides guidance on which biomass sources are, according to our criteria, generally harmless or potentially problematic. We then subject almost all of these biomass sources to a quantitative analysis. We first calculate the share of biomass from residues that can be classified as environmentally and socially compatible in the individual countries, using a combination of our own questionnaires, interviews with agricultural experts, and external studies. In a second step, we deduct the share that is already used as animal feed, fertiliser, raw material or for small-scale energy production. We also use interviews and studies for this purpose. If no data on alternative uses is available, we only take into account the share of residues that is currently burned and is therefore reliably available. This results in a comprehensive quantitative framework for various types of biomass from residues in countries of the Global South.

Using this three-step approach – comprising expert interviews, country-specific specialist literature and cross-country studies – our analysis goes beyond previous studies of global biomass potential. Furthermore, these studies either do not apply any sustainability criteria at all or address this central aspect in less detail. The criteria for environmental and social compatibility are not only suitable as a basis for the quantity estimates in this study. They can also be used as a set of criteria to assess individual quantities of biomass.

IV. Results: Available environmentally and socially compatible quantities of biomass from residues

Of the total seven billion tonnes of biomass from residues generated worldwide each year, only 6% meets our criteria for being environmentally and socially compatible and is available for our three climate applications. Agricultural residues make up the largest share, followed by residues from timber production, with dried sewage sludge accounting for the smallest share (Fig. b). Most of the suitable biomass is generated in Asia (excluding China, which we classify as an industrialised country), which, due to its large population, has a similarly extensive agricultural production.

Given our restrictive approach, it can be assumed that more biomass from residues is actually available for climate applications than has been identified here. It would be worth exploring whether biomass that has been completely excluded, such as sugarcane bagasse, might be acceptable in certain cases, and whether biomass remains wholly or partially available even if it is not burned. However, we can assume that these around 420 million tonnes are indeed environmentally and socially compatible and readily available. In practice, therefore, potentially suitable biomass from residues should always be assessed on a case-by-case basis.

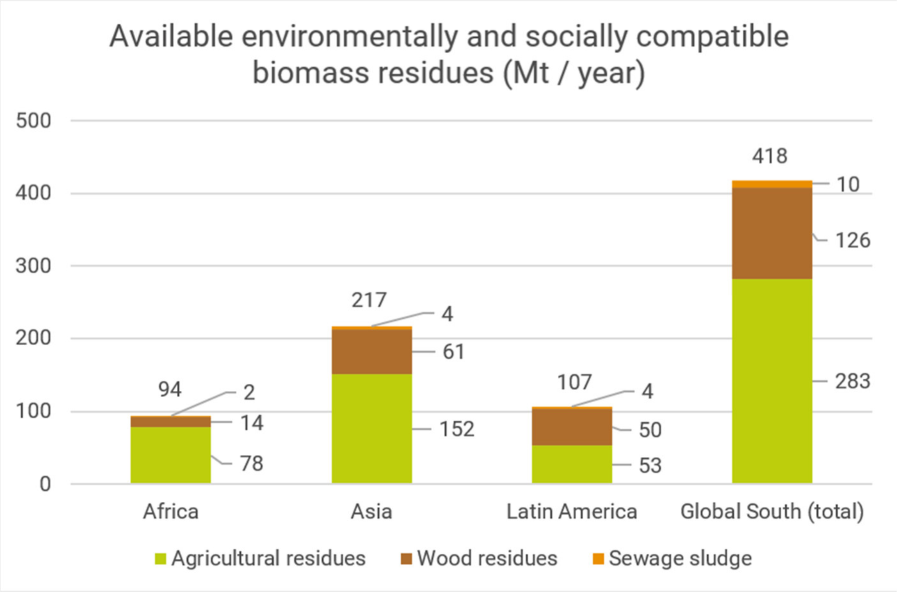

Figure b: Quantities of total available environmentally and socially compatible biomass by continent and across the entire Global South.

The share of this biomass that can be used economically depends on the costs involved and on whether it is generated at individual sites such as factories or at many sites distributed across the region. In a rough estimate, we conclude that around 40% of this biomass is generated at centralised sites and can be collected relatively efficiently if it is required at centrally located power stations or gasification plants. However, biomass generated at decentralised sites can also be used efficiently if it is used locally at village level.

You can request the complete data (quantities) used to calculate the biomass potential as a database by emailing peiker@atmosfair.de or info@atmosfair.de for a small fee.

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1. Introduction and goals

What humans are trying to achieve with sophisticated technology is a process plants have mastered over millions of years: plants capture carbon dioxide from the atmosphere and use solar energy to integrate that carbon into their physical structures. These organic compounds contain energy that can be used by humans. When the carbon in these compounds reacts with oxygen during combustion, the CO_2 released is equal to the amount captured by the plants during their growth.

These CO_2-neutral energy sources are an urgently needed alternative to fossil fuels: global warming must be limited to 1.5°C above pre-industrial levels to keep the impacts on people and the environment at a manageable level (IPCC 2018). atmosfair, an organisation dedicated to tackling climate change, helps in these efforts by establishing infrastructure to use renewable energy in developing and emerging countries in the Global South. These countries have historically contributed the least to global warming, but are particularly hard hit by the impacts of climate change because they lack the financial resources needed for climate adaptation. This is why these nations deserve to benefit from climate projects in the interest of North-South justice. atmosfair's projects go beyond climate measures and offer new opportunities for economic and social development. Solid biomass made from waste and residues[1] (agricultural, forestry and wood residues) plays a role in these efforts, which is why the total amount of biogenic residues available in the Global South is extremely relevant. This is the focus of our study.

Only genuine residues for biomass

We are aware that biomass can be problematic if the climate advantages come at the expense of sustainability. If farmers decide to grow more lucrative energy crops such as oil palms or sugar cane instead of food, this can jeopardise food security (food vs. fuel conflict). For this reason, our study does not look at energy crops. Instead we focus on "genuine" biomass made from waste and residues left over from food production, for example. These residues are only considered "genuine" if they are not used by people locally for other purposes, such as for animal feed, fertiliser, building materials or to meet household energy needs. These uses must be prioritised from both a social and an environmental standpoint. In addition, the crops that produce these residues should be grown using sustainable farming methods.

To uphold the principle of sustainability as defined in the United Nations Sustainable Development Goals (SDGs), we only consider biomass that is environmentally and socially compatible. For example, growing crops that yield usable waste should not endanger biodiversity or degrade soil quality through the excessive use of pesticides or fertilisers. We want to ensure that financial incentives do not encourage environmentally harmful farming practices that prioritise growing crops solely to generate residues.

Solid biomass: a versatile solution for combating climate change

In our study, we only look at solid biomass made from residues such as straw or wood residues and not wet residues like food waste or manure, as the available quantities are easier to quantify. This biomass can be used in three different ways to mitigate climate change:

- Combustion or gasification for electricity and heat: Solid residues can be burned directly in power plants. Gasifying solid biomass achieves greater efficiency for electricity generation than traditional combustion.
- Pyrolysis for negative emissions: Pyrolysis can be used to produce pure carbon from crop residues. When mixed with nutrients, this biochar can

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[1] "Biomass" in this study refers exclusively, unless otherwise specified, to solid biomass from agricultural, forestry and wood industry residues as well as dried sewage sludge.

improve the fertility of farmland while permanently sequestering carbon in the soil.

- Gasification for CO_2-neutral hydrocarbons: The biomass-to-X (BtX) process converts dry, solid biomass to gas via Fischer-Tropsch synthesis to produce hydrocarbon chains of varying lengths. Most of the resulting gas can be converted to jet fuel, for example, in refineries. When combusted, this biomass-to-liquid (BtL) kerosene releases an amount of CO_2 equivalent to what the plants absorbed during their growth.

BtL kerosene for the energy transition in aviation

In 2022, aviation accounted for 800 million tonnes of CO_2 emissions (IEA 2023). However, we currently lack the technology to completely decarbonise the sector, meaning that GHG emissions in aviation are considered “hard-to-abate”. In the short and medium term, aviation can only become CO_2-neutral through the use of sustainable aviation fuels (SAF). But we still have a long way to go: while global kerosene demand amounted to 280 million tonnes in 2023 (Statista 2024), only half a million tonnes of SAF were produced in the same year. However, this was twice as much as the year before (IATA 2023).

BtL kerosene is particularly attractive in this scenario because it can be produced from waste and residues, which do not involve the “food vs. fuel” conflict, unlike energy crops. Furthermore, the technology for BtL kerosene is either already available in countries in the Global South or can be established there relatively easily. This is not the case with power-to-liquid (PtL) kerosene. PtL is another form of synthetic fuel made from green electricity, water and CO_2 from the atmosphere.

Even though we consider synthetic kerosene produced using BtL processes as a potential means to mitigate climate change with biomass, we expressly distance ourselves from the use of synthetic fuels in road transport. Electrically powered vehicles are preferable to internal combustion engines on roads, as they are more efficient. As production capacities for synthetic kerosene will likely remain limited for quite some time, it should only be used where there are no alternatives (yet), such as in the aviation sector.

Structure of this study

An overview of the technical background for different climate applications is first provided followed by a summary of previous studies on the potential of these types of biomass made from waste and residues. The methodology of the study is then explained and its scope defined, both in terms of the biomass analysed and the countries covered. In Chapter 3, we outline a series of criteria used in Chapter 4 to conduct a qualitative analysis of environmental and social compatibility and availability of various types of biomass. In a second step, we quantify the potential of biomass available for climate applications (Chapter 6). We do not estimate future quantities of biomass, but rather those currently available in countries of the Global South. The sustainability criteria used in this study go beyond previous research. We use data from our own questionnaires and interviews with agricultural experts from the Global South to supplement extensive data and literature sources. We conclude with a discussion highlighting the relevance of the biomass potential for climate applications (Chapter 7). We also discuss the economic potential of biomass, which, although not the main focus of this study, is still relevant.

2. Background and methodology

2.1. Climate applications for solid biomass from residues

When used to generate energy, biomass is essentially carbon-neutral, as the carbon dioxide emitted during combustion was already absorbed from the atmosphere by the plants (Fig. 2). This is true for both biomass and energy crops grown specifically for energy production. Palm oil, maize and sugar beet contain particularly high levels of energy-rich compounds such as fats, starch and sugars (O'Malley *et al.* 2021, 2). But these crops are also controversial because they compete for land with food crops (the "food vs. fuel" debate).[1]

Energy crops compete with food crops

Energy crops can directly displace food production (direct land-use change, dLUC), particularly when other areas such as forests or pastures are cleared or ploughed to expand farmland. "Indirect land-use change" (iLUC) occurs when agricultural land previously used to grow food is instead used to farm energy crops, and natural ecosystems (e.g. forests or savannahs) are cleared elsewhere to cultivate these food crops. This problem is exacerbated by a global increase in demand for food in general and by rising meat consumption (WBGU 2009). A significant driver of iLUC is the higher profitability for farmers of energy crops compared to food crops.[2] When additional income opportunities like this emerge in a region, the price of food rises due to scarcer supply, which is particularly problematic for lower-income groups. The three competing uses of land (food security, climate change mitigation and biodiversity conservation) is called the "land-use trilemma" and must be taken into account when using biomass. In theory, sustainable land use can offer a way out of this trilemma (WBGU 2020, 40).

In this context, growing energy crops on degraded land is generally of interest, particularly where food crops are no longer grown because the soil's fertility has significantly deteriorated. In this case, there is no competition with food production, at least in theory. However, growing energy crops may not threaten local biodiversity. From a climate perspective, it is not always a good idea to grow energy crops on degraded land. In some cases, it can be more efficient to install solar panels on unused land (Rettenmaier *et al.* 2018, 99f.). As it is difficult to assess, from a global perspective, whether available land is actually degraded and whether restoring this land might not be more sensible for ecological reasons, we have not considered energy crops on degraded land. In this study, we therefore focus solely on solid residues.

Converting solid biomass to electricity

The main ways to use biomass for climate change mitigation are shown in Figure 1. This study focuses on dry, solid residues, because the data available for calculating them is significantly better than for wet residues, with the exception of sewage sludge. However, wet residues also offer significant potential for climate applications. They are digested to produce biogas, from which CO_2 can be captured. The methane in biogas can in turn be combusted to generate electricity or converted to carbon-neutral fuel. Solid residues are easiest to use in biomass power stations from a technical standpoint. They are combusted there to power steam turbines for electricity generation. Combined heat and power plants then use the steam to heat buildings in the form of district heating. This way, they use a significantly larger share of the energy contained in the biomass than pure biomass power stations. The efficiency of a biomass power station is higher if the resides are first converted to gas, and the gas is then combusted to generate electricity (Roos 2010, 5).

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[1] Algae can also be used to produce energy. Since algae cultures do not compete for farmland, they are less problematic from an environmental and social perspective. However, algae cultures for energy production are currently still in the experimental stage, so it is not yet possible to determine how much production potential there is.

[2] It is important to note that some energy crops, such as maize and soybeans, can be used both as food for humans and for energy production. While competition is for use, not for land, the problem is essentially the same.

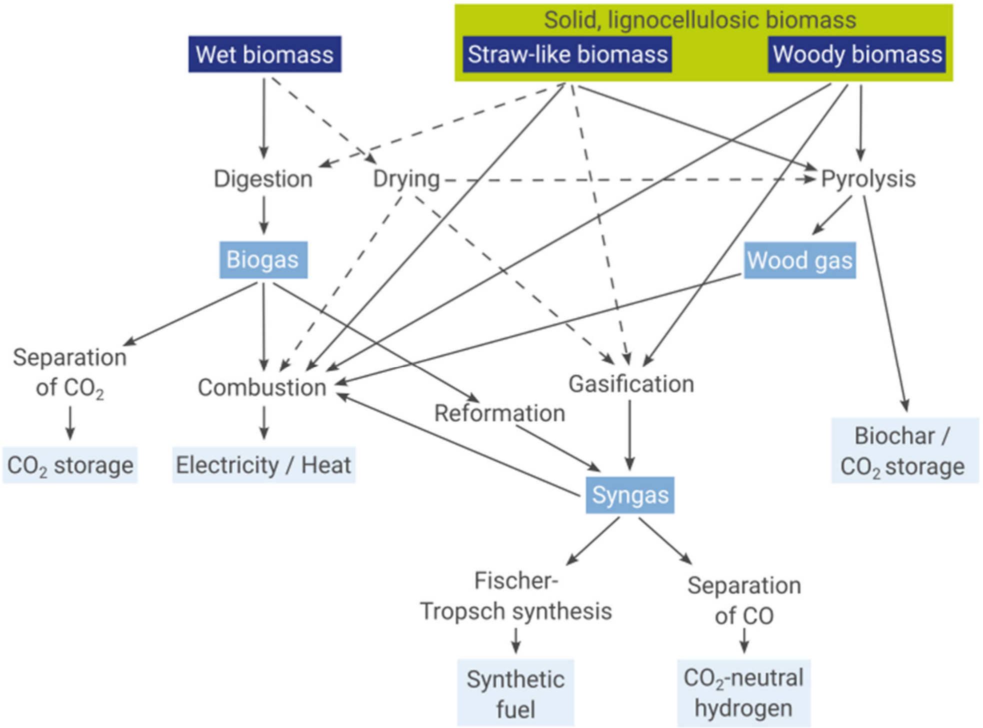

Figure 1: Possible pathways for energy generation and CO_2 storage with biomass from residues. As there are still challenges associated with thermochemical gasification of straw-like residues or dried wet residues, these arrows are shown as dotted lines. Composting of wet food waste is not covered in this study, as this does not constitute energy use, even though it also contributes to climate change mitigation.

Biomass power stations can prevent the emissions that occur when fossil fuels such as coal or natural gas are combusted in power stations.

Biochar for negative emissions

While the conversion of biomass to electricity can theoretically reduce greenhouse gas emissions to zero, biomass converted to biochar can even result in negative emissions. To make biochar, solid residues such as straw or wood must be heated up in an environment with virtually no oxygen. During this pyrolysis, flammable gases are released from the plant material and pure carbon remains. This biochar has a distinctive microstructure that retains nutrients and water. When mixed with nutrients and applied to fields as fertiliser, it improves soil fertility. It is also chemically inert and does not react with potential reactants. This way, the carbon that plants absorbed from the atmosphere's CO_2 during their growth remains permanently in the soil. The pyrolysis gas can also be used as an energy source

There are essentially two different ways to make biochar. Wood gasification stoves make it possible to produce biochar decentrally in households. During production in industrial plants, large quantities of residues are pyrolysed centrally.

CO_2-neutral kerosene from the biomass-to-liquid process

The biomass-to-liquid (BtL) process is one way to produce synthetic kerosene (Box 1). Synthetic fuels are CO_2-neutral when combusted, which is why the IPCC, among others, supports the production and use of synthetic fuels in aviation to achieve the climate target of 1.5 degrees (IPCC 2022, C.8). Unlike other sustainable aviation fuels, such as fat- and alcohol-based fuels derived from energy crops, BtL kerosene does not compete with food production (Matschegg *et al.* 2023, 11f.). In contrast to the PtL process, the energy required for the synthesis can be taken from the biomass itself. As a result, this process does not generally require energy externally, although additional energy can help stabilise the process. In the BtL process, solid biomass is thermochemically converted to gas at temperatures of up to 900°C, with only a limited supply of oxygen (Slatter *et al.* 2022). The molecules break down into smaller components and the carbon partially oxidises, resulting mainly in hydrogen and carbon monoxide. This synthesis gas is then converted in the Fischer-Tropsch process to hydrocarbons of varying chain lengths, ranging from one to 40 carbon atoms (Mahmoudi *et al.* 2017, 15). These are used as feedstock for kerosene, but also serve as raw materials for other fuels and the chemical industry. As an alternative to Fischer-Tropsch synthesis, solid residues can also be

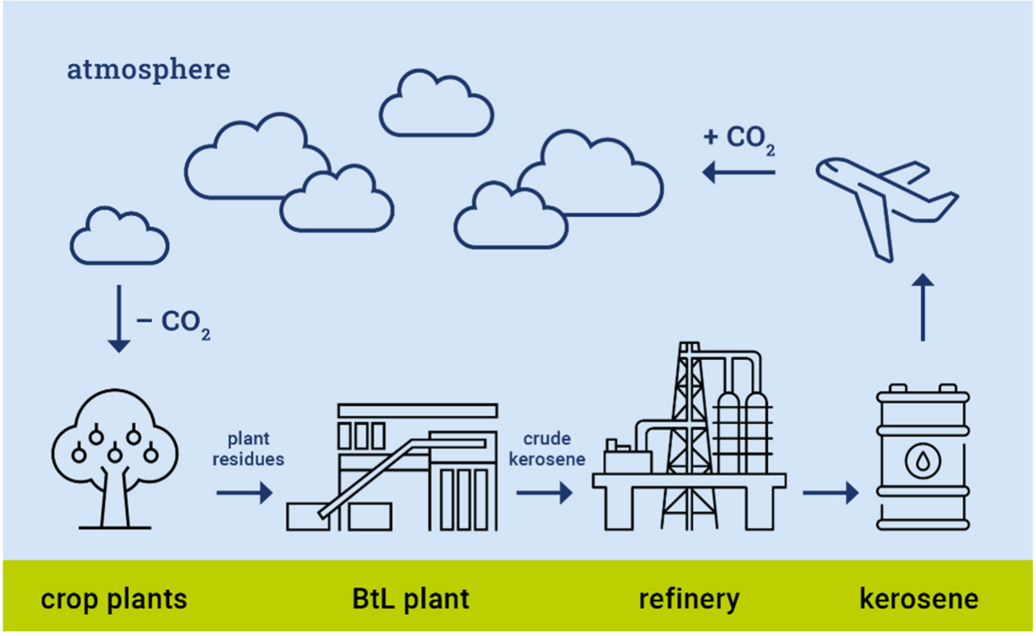

Figure 2: Diagram of the closed carbon cycle when using synthetic kerosene produced using BtL

converted to ethanol and methanol, which can also be used as fuel (Hauschild *et al.* 2023, pp. 21ff./91ff., van Dyk/Saddler 2024, pp. 33ff.).

The BtL process is currently still in the pilot phase. Overall, it stands at level seven out of nine on the Technology Readiness Level (TRL) scale, although certain parts of the production line are already more advanced than the process as a whole (DBFZ 2024, Hauschild *et al.* 2023, pp. 66ff.). Production on an industrial scale is not yet possible. However, trials show that this principle works, at least for biomass with certain properties: For example, in September 2024, atmosfair's affiliate Solarbelt gGmbH, in collaboration with the Austrian company BEST GmbH, successfully produced synthesis gas for the first time from cashew shells, which occur as waste products in the Ivory Coast. It should be possible to use other woody biomass in a similar way. However, it is not yet certain that straw-like biomass is equally suitable for gasification, as practical trials have yet to be carried out. Experiments such as the production of pyrolysis slurry (Mielke *et al.* 2020) or mixing with woody biomass give reason to expect that technical progress will also be made in future when it comes to processing “more difficult” residues.

Compared to PtL, BtL has the advantage that countries in the Global South not only have the

Box 1: Sustainable aviation fuels

The European Commission has introduced targets for carbon-neutral Sustainable Aviation Fuels (SAFs) as part of its ReFuel EU initiative to decarbonise aviation. The aim is for these sustainable aviation fuels to account for 6% of all aviation fuels delivered to EU airports by 2030 and 7% by 2050. SAFs include:

- Kerosene from hydrotreated esters and fatty acids (HEFAs): is produced from either oil-bearing plants like oil palms or rapeseed or from waste fats
- Alcohol-to-jet kerosene (AtJ): fuel made from ethanol, which is produced by fermenting sugars from energy crops such as sugar cane or maize
- Power-to-liquid kerosene (PtL): synthetic kerosene; made with water, carbon dioxide from the air and electricity from renewable energy
- Biomass-to-liquid kerosene (BtL): synthetic kerosene; made from solid biomass by gasification to produce synthesis gas, followed by Fischer-Tropsch synthesis

As energy crops are problematic from an environmental perspective, the European Commission has also introduced targets for synthetic fuels, which can be produced without the need for specially grown energy crops. The target is for BtL and PtL kerosene to account for 35% of total kerosene by 2050, which is half of the mandatory share for sustainable fuels (European Parliament and Council 2023b).

necessary residues, but in some cases also the infrastructure for gasification and Fischer-Tropsch synthesis. The closed CO_2 cycle of BtL kerosene is shown in Figure 2. It is important to bear in mind that the environmental impact of flying is not limited to CO_2 emissions alone. Aviation emissions contain nitrogen oxides and soot particles that form ozone, cause contrails and contribute to global warming. Overall, the actual climate impact of aviation emissions is two to three times greater than the impact of CO_2 alone (Niklaß *et al.* 2020). That is why even CO_2-neutral kerosene is not climate-neutral. However, its chemical composition can be modified to reduce the amount of nitrogen oxides and soot particles produced during combustion compared to fossil fuels (van Dyk/Saddler 2024, 16ff.).

2.2. Studies to date on the potential of biomass from residues

In the past, several studies have quantified the potential of global biomass from residues. This biomass was often considered alongside energy crops and other energy-rich materials to calculate the total bioenergy potential. However, we do not think that the sustainability criteria used in the studies are sufficient. Table 1 summarises important analyses conducted to date on the energy potential of biomass from residues.

This table shows that, on a global scale, biomass from residues exists with an energy potential of approximately 20 to 280 exajoules (EJ, i.e. 20 to 280 trillion joules). This range reflects the considerable uncertainty inherent in these kinds of estimates. This is due, among other things, to the types of biomass taken into account, the different reference periods, the methodology used to estimate the potential and the sustainability criteria applied, which further limit the available quantity. The Global Energy Assessment (GEA) also reflects the fact that agricultural production will increase in future. It therefore forecasts energy potential for 2050 that are more than 50% higher than the current potential of the GEA (Rogner 2012, 482ff.).

The studies to date take into account the energy potential of the entire world, including major agricultural producers like China and the USA. That is why the study focuses exclusively on biomass in the Global South. Furthermore, some of the studies conducted to date apply either no sustainability criteria at all, inadequate criteria or criteria that are not sufficiently transparent in their calculations. The study by the Energy Transitions Commission (ETC 2021) goes the furthest in this regard. It takes into account only wood residues from sustainably managed forests and uses comprehensive criteria to assess the environmental and social compatibility of energy crops. However, the study does not apply these criteria to biomass, which it generally classifies as sustainable (ETC 2021, 18). The 2009 report by the German Advisory Council on Global Change (WBGU) estimates the total sustainable technical potential of biomass from agricultural and forestry in the year 2050 to be 50 EJ per year. However, the authors emphasise that this figure is extremely uncertain and further research is needed (WBGU 2009, 104ff.). The study further recommends that “the use of wastes and residues be given clear priority over the use of energy crops” (WBGU 2009, 326) and thus validates our approach. The Concawe study uses sustainability criteria recognised under the Renewable Energy Directive (RED) II, which are comprehensive in scope; however, it uses these criteria solely to calculate the potential of sustainable biomass for the European Union (Panoutsou/Maniatis 2021).

Determining different biomass potential

While the GEA identifies only an undefined “extractable” quantity, the International Energy Agency (IEA), the World Economic Forum (WEF) and the ETC take specific alternative uses into account. They exclude agricultural residues that are already used as feed or fertiliser for erosion control or as fuel, even if this figure is based only on rough estimates (Eisentraut 2010, Wolff/Riefer 2020). In their study on the production of sustainable aviation fuels in the EU, O’Malley *et al.* (2021) also point out that some of biomass is used to improve soil nutrient levels and should consequently be left on fields or in forests. However, these sustainability criteria do not take into account all the relevant aspects of the principle of sustainability. Our study discusses this in more detail in Chapter 3. The total amount of all biomass that is actually available in a region and has no other use can be described as the “technical potential” (Box 2).

Table 1: Overview of selected studies on the global energy potential of biomass

Study	Reference year	Energy potential of biomass	Types of biomass analysed	Sustainability criteria
German Advisory Council on Global Change (WBGU) “World in Transition: Future Bioenergy and Sustainable Land Use (WBGU 2009)	2050	approx. 80 EJ/year total, approx. 50 EJ/year sustainable	Agricultural residues, wood residues, animal manure, municipal waste	List of environmental and social guide rails, but only a rough estimate of the sustainable potential
International Energy Agency (IEA): “Sustainable Production of Second-Generation Biofuels” (Eisentraut 2010)	2030	approx. 140 EJ/year total, approx. 35 EJ/year unused[1]	Agricultural and wood residues	Only unused agricultural and wood residues are taken into account (25% of the total volume of agricultural and wood residues)
Intergovernmental Panel on Climate Change (IPCC): “Bioenergy” (Chum *et al.* 2011)	2050	approx. 25-280 EJ/year	Agricultural residues, wood residues, municipal waste, animal manure	List of environmental/social aspects, but potential for sustainability is not quantified
Global Energy Assessment (GEA) Council: “Global Energy Assessment - Toward a Sustainable Future” (Rogner 2012)	2050	approx. 120-135 EJ/year	Agricultural residues, wood residues, municipal waste, animal manure	No sustainability restrictions; only “extractable” potential is taken into account
World Economic Forum (WEF): “Clean Skies for Tomorrow - Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation“ (Wolff/Riefer 2020)	2030	approx. 45 EJ/year sustainable[2]	Agricultural residues, wood residues, municipal waste	Only unused agricultural residues are taken into account; wood residues from primary forests or protected areas are excluded
Energy Transitions Commission (ETC): “Bioresources within a Net-Zero Emissions Economy“ (ETC 2021)	2050	approx. 20-40 EJ/year sustainable	Agricultural residues, wood residues, municipal waste, animal manure	Only unused agricultural residues are taken into account; wood residues from unsustainable forests are excluded; animal manure only from humane livestock production and where there are no alternative uses

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[1] Author’s calculation of the energy content of dry matter

[2] Author’s calculation of the energy content of dry matter

Box 2: Different types of biomass potential

The following definitions are based on Brosowski 2021 (pp. 5-6) and WBGU 2009 (102ff.). However, it is important to note that the terms have not always been used consistently in previous publications.

Technical potential: The amount of biomass that can actually be used in a given region without competing with other uses.

Economic potential: The amount of biomass that can actually be used profitably. Both the procurement costs for biomass and the revenue that can be generated from the use of biomass must be taken into account here. This means that the economic potential is less than the technical potential.

Environmentally sustainable potential: The amount of biomass that is acceptable from an environmentally sustainable perspective. It is important to note here that not all sustainable biomass can be used profitably. On the other hand, not all economically usable biomass from residues is environmentally compatible.

2.3. Study methodology

The wide range of findings from previous studies highlights the urgent need to assess the specific technical and environmental sustainability potential of genuine biomass that can be harnessed to mitigate climate change. Figure 3 is a diagram illustrating the methodology of this study. In several steps, we focus on a subset of all biomass from residues that, according to our criteria, is particularly suitable for electricity generation, kerosene production or as feedstock for biochar:

1. Only solid residues: Of the total global volume of all residues, we focus initially on solid biomass from residues.
2. Developing countries only: As a second step, we select solid biomass from countries in the Global South. Biomass from industrialised countries is not taken into account.
3. Environmental and social compatibility: We determine the amount of biomass that can be considered acceptable from an environmental and social perspective. Certain problematic types of biomass are completely excluded, while others are only partially included in the quantity estimate.
4. No competing use: In the next step, we exclude all environmentally and socially compatible biomass sources that are already being used for other purposes and are therefore unavailable. This allows us to assess both the technical and environmental sustainability potential.
5. Economic viability: In the final step, we determine the economic potential of the biomass. Only part of the environmentally and socially compatible quantities that are available can actually be used for economic purposes. As this potential cannot be accurately quantified, we offer some basic insights into how it could be estimated and assume that centrally and semi-centrally generated residues can be transported and used more efficiently than those generated locally.

Assessment of environmental and social compatibility and availability

The study focuses on assessing the environmental and social compatibility of biomass on the one hand and its availability on the other. To this end, we use both a top-down and a bottom-up approach:

1. Top-down approach: identification of the principles and criteria for sustainable biomass based on the UN's Sustainable Development Goals (SDGs).
2. Bottom-up approach: identification of environmentally and socially compatible, usable biomass by assessing these criteria for various types of biomass through interviews conducted with agricultural experts and by consulting the relevant literature sources.
3. Quantity estimate: calculation of the amount of environmentally and socially compatible and available biomass based on statistics and information from the bottom-up approach.

The Sustainable Development Goals, which outline the objectives of the United Nations' 2030 Agenda, serve as the basis for the top-down approach (UNGA 2015). As they take into account environmental, social and economic aspects, this is a comprehensive and widely recognised source for defining principles for sustainability. Based on these goals, principles are derived that are relevant for identifying suitable biomass, as well as clear criteria for evaluating the various types of biomass. The principles and criteria are set out and explained in detail in Chapter 3. Using these criteria, various specific types of biomass are subjected to a critical assessment of their environmental and social compatibility as part of a bottom-up approach. However, it is important to note that there is no such thing as an ideal situation where crops (and thus biomass) are entirely free of environmental and social impacts.

atmosfair’s climate projects in countries of the Global South give the organisation the opportunity to conduct interviews with agricultural experts. They provide insights into the environmental and social compatibility of biomass where this is not possible from the relevant literature. This determines which types of biomass are generally environmentally and socially compatible, environmentally and socially compatible depending on circumstances or mostly not environmentally and socially compatible. The latter are not taken into account in the subsequent quantitative assessment.

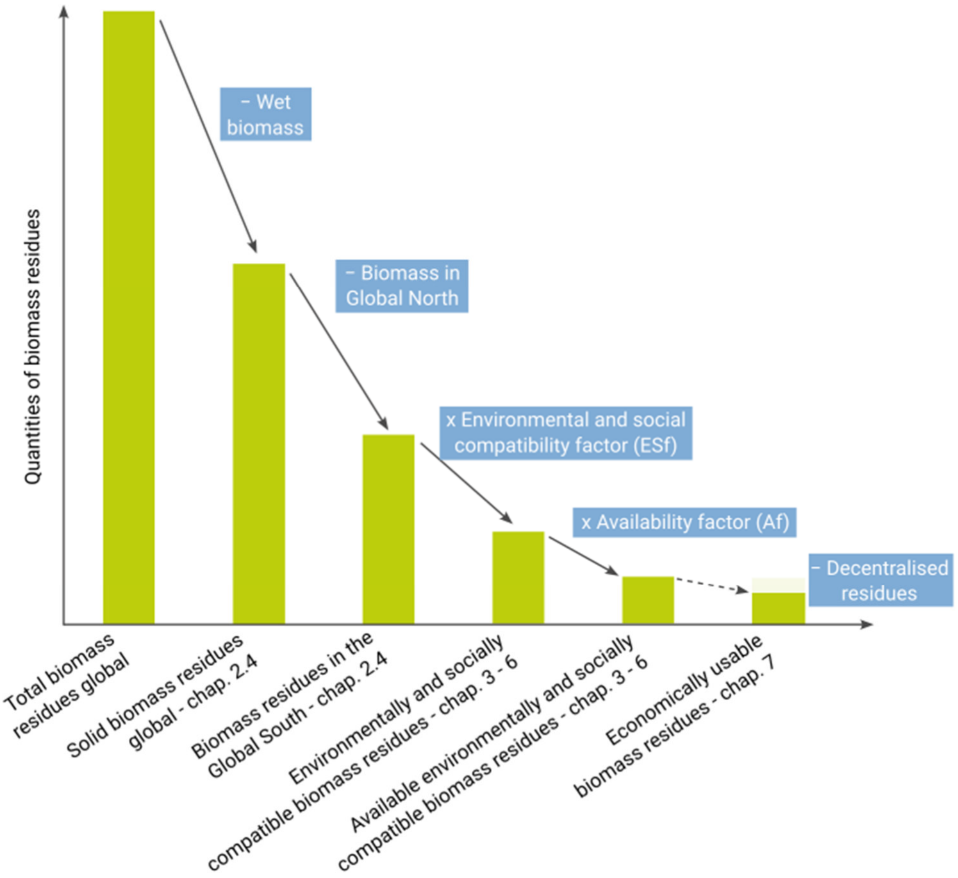

Figure 3: Methodology of the study, gradually limiting the scope to biomass that is particularly suitable for use

Basic principle of conservative estimates

To estimate the usable quantities of various crops and sawn wood, this study first draws on the database of the Food and Agriculture Organization of the United Nations (FAOSTAT 2024). The empirical part of this study follows the principle of “conservative estimates”, meaning that, from the range of available data, lower rather than higher percentages are selected for the available environmentally and socially compatible biomass. This means that actual quantities are more likely to be underestimated than overestimated, thereby increasing the certainty that the calculated quantities can actually be used. Overestimating the potential poses the risk of excessive strain on natural resources, with the associated environmental and socio-economic risks.

How quantities are estimated

Quantities are estimated in a table where each row represents a specific crop (or wood product or treated wastewater) in a particular country. Each row contains a multi-stage estimate of the environmentally and socially compatible and available biomass, following the approach shown in Figure 3. In a first step, the total mass of the actual crop produced is multiplied by the residue-to-product ratio (RPR), which indicates how much biomass is produced in relation to the product mass. The moisture content is also deducted from the biomass, as only solids can be gasified.

Particularly in the case of biomass, which, according to the qualitative assessment, is only environmentally and socially compatible under certain circumstances, it must be assumed that only part of it can be taken into account. To determine this percentage, we multiply the total biomass by the environmental and social compatibility factor ESf. Even in the case of environmentally and socially compatible biomass, the assumption must be that it cannot be fully harvested and used, as some of it is used for purposes that are prioritised over energy production. We then multiply the environmentally and socially compatible biomass by a further availability factor *Af* to obtain the available, environmentally and socially compatible biomass. The complete formula for estimating the quantity is as follows:

$$M_{\text{usable biomass}} = M_{\text{farmed crop}} * RPR * \text{dry share} * ESf * Af$$

The RPR value can be taken from the literature (in particular Koopmans/Koppejan 1997, Ojolo *et al.* 2012, Yevich/Logan 2003). We determine the values for *ESf* and *Af* using four different types of sources, which vary in terms of accuracy. Only if a value cannot be derived from a more accurate source is a source from the next, less accurate level used. These are the four priority levels of the sources:

1. Expert interviews with quantitative questions, conducted specifically for this study, are the most accurate source for determining the environmental and social compatibility and availability, of individual crops in individual countries. This data takes precedence over other sources, but is only available for some crops and countries.
2. If no interviews are available for specific crops in specific countries, interview data is extrapolated where possible to countries that are comparable in terms of their geographical location and the general environmental and social compatibility of their agriculture.
3. If interview data from comparable countries cannot be applied to specific crops in individual countries, we draw on specific literature sources. However, unlike our expert interviews, these do not use standardised questions or criteria.
4. If no specific literature sources are available for individual crops in specific countries, we draw on global studies or statistics that provide information on the percentage of environmentally and socially compatible agricultural production, or on the percentage of biomass burned on fields or at field edges, for individual countries or regions of the world. It can be assumed that biomass, which until now has been burned outdoors, can certainly be used for BtL production.

2.4. Types of biomass and countries covered by the study

This chapter focuses on the first and second steps in Figure 3 and describes how the biomass types and countries covered by this study were selected.

The technologies combustion, pyrolysis, and gasification are highly suitable for converting lignocellulosic, solid residues – both woody and straw-like – to energy and fuels. Among these, woody residues like cashew shells, cotton stalks and wood chips from sawmills are particularly well-suited for biomass-to-liquid (BtL) processes to produce kerosene. Because of their composition, these residues are well-suited for gasification, breaking down into the hydrogen and carbon monoxide needed for fuel production. Straw residues, on the other hand, are less suitable for gasification due to their high ash content. However, experiments have shown that straw can be effectively gasified when co-fired with a small amount of wood residues. Alternatively, straw can first be converted to pyrolysis slurry prior to gasification (Mielke *et al.* 2020) However, this technology is not yet commercially viable.

Exclusion of wet biomass

Wet biogenic residues such as household waste, animal manure or garden waste are also produced in large quantities; these have so far often gone unused and emit methane during decomposition. Their use would not only generate energy and prevent the consumption of fossil fuels, it would also reduce emissions of a greenhouse gas that is 27 times more harmful to the climate than CO_2 over a 100-year period. However, they are not included in this study because the data on the volume of wet residues, as well as their environmental and social compatibility and availability, is less reliable than for solid residues. One exception among wet residues is sewage sludge, the volume of which can be determined from a global study on the volume of treated wastewater (Jones *et al.* 2021). The most common use of sewage sludge is

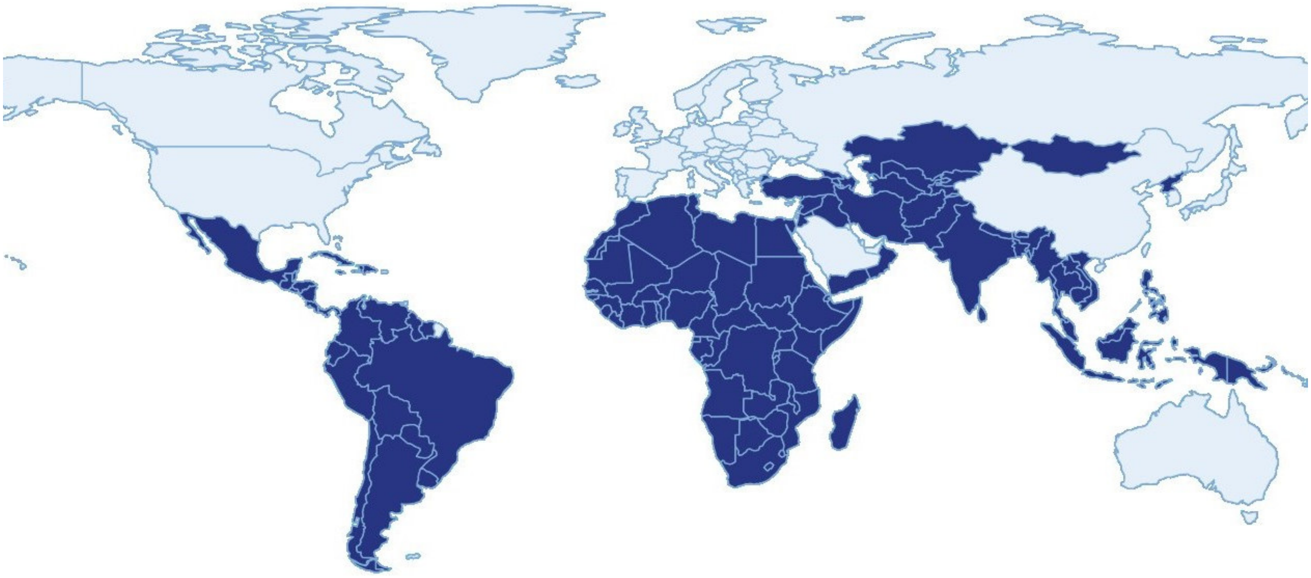

Figure 4: Countries considered for estimating the biomass potential from agriculture residues

digestion to produce biogas, which is used in generators to produce electricity. In dried form, however, it is also suitable for the same climate applications as solid residues, meaning we can compare its usability directly with agricultural and wood residues. As sewage sludge is produced in concentrated form in wastewater treatment plants, it can be dewatered there relatively efficiently using centrifuges or presses and then dried (CUTEC Institute 2017, 44ff.). Even the production of biochar is technically possible using dried sewage sludge. This even gives it an advantage over biochar, as phosphorus – an important nutrient – is already present in the raw material and does not need to be added later (Ledakowicz *et al.* 2019).

This study looks at the following residues:

- Agricultural residues: This refers to biomass that occurs as residues in agriculture or in companies that process agricultural products. This term covers biomass from a wide variety of crops, either from woody or straw-like residues. Furthermore, we assume that this category accounts for the largest total volume, which is why it is the main focus of this study.
- Wood residues: These are primarily residues that occur when wood is processed in sawmills and have no practical use. Residues from clearing shrubwood and wood harvesting residues can generally also be used for climate applications.
- Sewage sludge: Dried sewage sludge, which is produced when wastewater is purified in treatment plants, also has the potential to be combusted as an environmentally and socially compatible residue in biomass power stations, gasified in BtL plants or converted to biochar by pyrolysis.

Focus on the countries of the Global South

In line with the geographical focus of atmosfair's climate projects, this study focuses on biomass in Latin America, Africa and most Asian countries, although solid biomass is also available for climate applications in industrialised countries (Fehrenbach *et al.* 2019, Panoutsou/Maniatis 2021, pp. 8-9). However, in the Global South, it must be kept in mind that local populations need certain types of biomass to improve soil quality, for use as raw materials, as animal feed or as fuel in their households. This means they need to grow fewer feed crops or use fewer fossil fuels. Using these materials to improve soil quality (mulch, fertiliser, compost) lowers the use of artificial fertilisers, while carbon remains sequestered in building materials for a long time.

We only include biomass that is unsuitable for these alternative uses in our estimated quantities. It is up to the local communities to decide which climate applications these residues will ultimately be used for. In many cases, the priority is supplying local energy through biomass power stations or improving soil quality using biochar. However, it could also be a viable strategy to produce BtL kerosene from biomass rather than combusting the residues directly to generate electricity. Kerosene is a higher-quality form of energy and can be exported at high prices – if there is no domestic demand – which is an important source of income, particularly for economically weaker countries. In theory, the earnings from these exports could be invested in the development of an electricity infrastructure – preferably using renewable energy sources like solar. This is only possible if BtL production yields higher profits than electricity generation. Rising prices for aviation fuel in future could be a factor here.

The estimate includes a total of 111 countries, which is only some of the countries that are considered part of the Global South (UNCTAD 2022). We do not include China, as it has produced the second-highest cumulative greenhouse gas emissions of any country (Our World in Data 2023). Responsibility for mitigating climate change lies with those countries that caused global warming rather than those most affected by it. In the interest of North-South justice, these high-impact regions should be the primary beneficiaries of climate projects In the Global South, we also exclude wealthy countries that have sufficient financial resources for climate adaptation measures and climate projects, primarily those on the Arabian Peninsula.[1] Furthermore, we do not include small island nations, as their total amount of biomass is insignificant and there is little data on the availability and environmental and social compatibility of this biomass.[2] The map below (Fig. 4) shows all countries covered in our study.

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[1] All countries in the Global South, as defined by UNCTAD, with a per capita income of over 25,000 US dollars in 2023 (UNSD 2024), specifically: Bahrain, Brunei Darussalam, Kuwait, Qatar, Saudi Arabia, Singapore, United Arab Emirates.

[2] All island nations with a population of less than two million (UN DESA 2024).

3. Derivation of principles and criteria for the use of biomass

3.1. The Sustainable Development Goals as a basis for evaluation

This section outlines the principles and criteria for the third and fourth steps in the process shown in Figure 3 (Chapter 2.3), which involve limiting the scope to environmentally and socially compatible, as well as available biomass (i.e. "genuine residues").

The EU's RED II Directive includes environmental criteria such as biodiversity conservation and greenhouse gas (GHG) emissions, but contains no specific provisions on the social and economic aspects of sustainability (European Parliament and Council 2023a, Art. 29). The Sustainable Development Goals (SDGs), which are the aims of the United Nations' 2030 Agenda for Sustainable Development, provide a better and more comprehensive basis for our study. The 17 SDGs apply to all countries and include not only environmental goals, but also social and economic ones (UNGA 2015). As a result, they are sufficiently comprehensive to allow sustainability principles to be derived for the purposes of this study. Table 2 lists nine criteria for identifying environmentally and socially compatible biomass arising from the production of agricultural crops.

3.2. Derivation of principles and criteria

Four principles for identifying sustainable biomass can be derived from the nine relevant goals in Table 2; these are explained in more detail in the following sections:

1. Prioritise land for food and biodiversity
2. Climate change mitigation and environmental protection
3. Protect and promote human rights and smallholder structures
4. Prioritise biomass for food, soil improvement, materials and small-scale energy generation

For each principle, we define specific criteria related to environmental and social compatibility, as well as availability that can be used to assess the various types of biomass.

3.2.1. Principle 1: Prioritise land for food and biodiversity

This principle is based on the SDGs for combating hunger and malnutrition and for protecting biodiversity, ecosystem services and habitats. Both goals are at risk because the cultivation of certain crops requires additional land, which is then unavailable for either food production or nature conservation. It is important to note that in both cases, the land-use change may be direct (direct land-use change, dLUC) or indirect (indirect land-use change, iLUC).

Criterion 1: Exclude energy crops

Fertile land is a limited resource that should be used primarily to ensure food security. Even now, the need for land exceeds the amount of land available globally. A particular problem is that energy crops grown for biofuel production are often portrayed as a sustainable alternative to fossil fuels, even though they compete with food production (WBGU 2020, 22ff.).

This food vs. fuel conflict also affects the usability of biomass. As a result, no plant residues used to produce biofuel (e.g. sugar cane, energy maize) should be used. Using residues from energy crop production would provide farmers with additional financial incentives to grow them. This would further reduce the amount of land available for food production. We also exclude residues from energy crops grown on degraded land.

Table 2: Sustainable Development Goals (UNGA 2015) relevant to determining the availability of sustainable biomass. The right-hand column sets out the principles for assessing biomass, which are derived from the respective goals.

Sustainable Development Goal	SDGs	Description	Derived principle for the assessment
Zero hunger and malnutrition.	2.1 – 2.2	The target here is to ensure year-round access to sufficient food by 2030. This also means ending malnutrition, which particularly hinders children's development.	P1 Prioritise land for food and biodiversity
Increase agricultural productivity and incomes.	2.3	The target is to double the agricultural productivity and income of smallholder food producers, particularly marginalised groups such as women and indigenous peoples. Secure access to fertile land plays a key role here.	P3 Protect and promote human rights and smallholder structures
Gradually improve soil quality.	2.4	The aim is to improve soil quality and protect ecosystems through sustainable food production. It is also important to increase resilience to extreme weather events such as droughts and floods.	P2 Climate change mitigation and environmental protection
Reduce the number of deaths and illnesses caused by environmental toxins.	3.9	To achieve this goal, it is necessary to reduce the use of harmful chemicals and to limit air, water and soil pollution.	P2 Climate change mitigation and environmental protection
Improve water quality and the efficiency of water use.	6.3 – 6.4	The aim is to improve water quality by reducing the use of chemicals and treating wastewater. Water must be used more efficiently in order to ensure a sufficient supply of drinking water.	P2 Climate change mitigation and environmental protection
Achieve efficient use of natural resources.	12.2	All usable materials arising from the production of agricultural products should be put to the best possible use.	P4 Prioritise biomass for food, soil improvement, materials
Take immediate action to combat climate change and its impacts.	13	Climate change must be combated by reducing greenhouse gas (GHG) emissions. For agriculture, this means that carbon should be removed from the air and stored in plants or the soil. In addition, GHG-intensive farming practices must be limited.	P2 Climate change mitigation and environmental protection
Protect and restore terrestrial ecosystems and promote their sustainable use.	15.1 – 15.3	Ecosystems and their biodiversity should be protected through sustainable forest management and preventing or reversing land degradation – including desertification – in agriculture.	P1 Prioritise land for food and biodiversity; P2 Climate change mitigation and environmental protection
Protect natural habitats.	15.5	The destruction of habitats must be stopped to preserve biodiversity and protect endangered species.	P1 Prioritise land for food and biodiversity

Box 3: The food vs. fuel conflict increases food prices

Food prices are an indicator of the food vs. fuel conflict. They have risen significantly since the demand for biofuels began to grow. For example, the price of maize tripled between 2005 and 2008, coinciding with the increased use of this crop for bioethanol production. During the same period, prices for other foods rose by around 50% because, on the limited amount of farmland available, maize was increasingly grown as a source of fuel, thereby reducing food production (Mitchell 2008, 3f.).

It is not possible to say with certainty whether these areas are actually too infertile for food production.. Furthermore, it would often make more sense to restore degraded land so that high-value ecosystems can emerge here in the long term. Our approach is therefore more restrictive than studies such as Wolff and Riefer (2020), which include oil crops on degraded land in their calculation of sustainable biomass potential.

Criterion 2: Preserve biodiversity

Our planet's biodiversity must be protected to preserve essential ecosystem services. Biodiversity is defined as the diversity of ecosystems, species diversity and genetic diversity (CBD 2024, Art. 2). However, natural terrestrial ecosystems are also endangered by the increasing land needed for food production and energy crops: the main causes of biodiversity loss include clearing forests and grasslands and draining wetlands. The more profitable a crop is, the greater the risk that high-value areas will be used for agriculture, thereby destroying their biodiversity.

High-value land ecosystems also include wetlands and, in particular, peatlands, which, in addition to their biodiversity, serve as CO_2 sinks. If they are drained for agriculture, large quantities of CO_2, as well as other GHGs like methane, are released into the atmosphere. When using biomass, it is therefore essential to ensure that it does not come from crops grown on land where high-value habitats have been or are being destroyed.

The example of sugar production in Brazil shows that land-use change can often occur indirectly (iLUC). This is the case when a field is no longer available for food production because it is used to grow energy crops instead, and natural ecosystems are displaced elsewhere to make way for food production (WBGU 2009, 219f.). This is how growing energy crops causes GHG emissions by contributing to deforestation, which negatively impacts the carbon footprint of this energy source (Hamelinck/Knotter 2021, 10ff.). That is why the principle "Prioritise land for food and biodiversity" must also exclude biomass whose cultivation has indirectly led to land-use change.

3.2.2. Principle 2: Climate change mitigation and environmental protection

Contrary to the UN's Sustainable Development Goals, certain agricultural practices reduce soil fertility or pollute water and air. This is particularly true for industrial agriculture, which operates on large areas of land with heavy use of machinery, fertilisers and pesticides. The use of biomass is acceptable as long as the negative environmental impacts of the associated agriculture and forestry remain within environmentally compatible limits.

Criterion 1: Protect soil

Higher demand for food increases the pressure to boost production on fertile land using industrialised farming methods. However, this can damage soil in many ways:

- The nutrient content of the soil is reduced by overuse. Large areas can also be damaged by wind and water erosion.
- Excessive use of mineral fertilisers can lead to soil acidification due to excess nitrogen, as well as pollution of water bodies (eutrophication) and groundwater.
- The use of pesticides can pollute soil and water.
- If artificial irrigation causes extensive evaporation, the soil may become salinated.
- The use of heavy agricultural machinery compacts the soil, reducing its ability to store water. This can cause droughts and floods.

Box 5: Indirect land-use change caused by sugar production

The growing demand for bioethanol since 2000 has made growing sugar cane more lucrative. The Brazilian Cerrado region offers ideal growing conditions for sugar cane, which leads to the ecologically valuable savannah being cleared for agriculture (dLUC). Pastures or soybean fields are also being sold to sugar producers. However, this expansion in sugar production leads to iLUC, as primary forests are being cleared on the edge of the Amazon region to make way for pastures and soybean production, thereby replacing the land in the Cerrado. Between 2002 and 2012, a total of 16,300 km² of forest was lost because farmers moved their activities out of the Cerrado due to the expansion sugar cane production. This loss of forest led to emissions of almost 200 million tonnes of CO_2 (Jusys 2017).

Industrialised agriculture can lead to biodiversity loss and land degradation (Birkhofer *et al.* 2021). Land degradation means the deterioration of all terrestrial systems: by 2018, 25% of the productivity of farmland, 23% of forests and 33% of pastureland had already been lost due to land degradation (Hill *et al.* 2018). Land degradation is a major problem, particularly on the African continent, because increasing pressure on land use has led to farming practices that do not allow sufficient time for soil regeneration. An estimated 45 million hectares are directly affected by the loss of soil nutrients. If the loss of soil and thus nutrients due to erosion is taken into account, 68% of African agricultural land is affected (Jones *et al.* 2013, 148ff.). To compound the problem, in East African countries with high or very high levels of soil nutrient loss, more than 25% of the total population suffers from malnutrition (Jones *et al.* 2013, 153ff.). Consequently, the risk of malnutrition and undernutrition increases when nutrients are not returned to the soil.

Box 4: Destruction of rainforests for oil palms

One example of especially severe direct destruction of natural habitats is the cultivation of oil palms in Borneo. Here, between 1975 and 2015, the expansion of plantations led to the destruction of 50% of the natural forests. More than 50% of the new plantation areas were established directly on land that was previously covered by forest (dLUC) (Meijaard *et al.* 2020).

Biomass from industrial agriculture requires a critical analysis of farming practices, keeping in mind that there will be virtually no biomass from entirely environmentally compatible cultivation. The use of mineral fertilisers, in particular, is almost impossible to avoid on nutrient-poor land. However, it is important to ensure that fertilisation does not lead to soil acidification.

Criterion 2: Protect water

Overfertilisation can harm not only the soil but also water bodies through eutrophication, leading to excessive algae growth and a loss of biodiversity due to oxygen depletion. Pesticides can harm both biodiversity and human health. Furthermore, intensive irrigation of agricultural land jeopardises the water supply for people and ecosystems. Agriculture accounts for the largest share of freshwater consumption, at around 72% of global demand. At the same time, more than 2.3 billion people live in regions affected by water stress, and 3.6 billion people have insufficient access to freshwater for at least one month a year (Cullmann *et al.* 2021, 5ff.). It is likely that this figure will continue to rise as the frequency of droughts increases.

In view of these problems, the assessment of the usability of biomass must take into account the amount of fresh water used and the potential impact on groundwater and surface water.

Criterion 3: Protect the air

When crop residues are burned outside on fields or slash-and-burn methods are practised, the air is polluted with particulate matter. High levels of particulate matter can lead to an increase in respiratory diseases and lung cancer among the local population. The practice of burning crop residues is widespread in South Asia, for example, in part to increase the nutrient content of the soil through the ash. At the same time, poor air quality poses a particularly high health risk to people in this region (Lin/Begho 2022).

Fire for land clearance is frequently used due to economic pressure and land conflicts. This poses a risk of the uncontrolled spread and escalation of forest fires, which cause massive air pollution from smoke. In Asia, this phenomenon is known as the Southeast Asian Haze. It has a negative impact on

Box 6: Environmental impacts of cotton production

Cotton production is particularly problematic in terms of freshwater resources. Although the plant itself is a perennial, it is grown as an annual in monocultures to maximise yields. Cotton is particularly susceptible to pests and weeds when grown as a monoculture, which is why large quantities of pesticides and herbicides are often used. Furthermore, cotton plants need a lot of water. The best yields are achieved in deserts with artificial irrigation, requiring an enormous amount of water: 3,600-26,900 litres per kilogram of cotton (Paulitsch *et al.* 2004).

human health and the economy in the affected regions (Purnomo *et al.* 2018).

Based on our principles, crop production must not pollute the air with particulate matter, which is primarily caused by slash-and-burn practices or burning crop residues on fields.

Criterion 4: Reduce greenhouse gases

It is not just industry, electricity generation and transport, but also agriculture that generate GHG emissions. This is partly due to the use of mineral fertilisers, which give rise to GHG emissions both during their production and when applied to fields. During microbial decomposition, nitrous oxide (N_2O) is produced, which has a global warming potential 300 times greater than that of CO_2. The use of machinery causes carbon dioxide emissions from fossil fuels. However, it must also be kept in mind that organic farming is less productive, and the GHG intensity for a specific quantity of agricultural products can therefore be higher than in conventional farming (WBGU 2020, 140ff.). That said, we generally assume that, when all environmental aspects are taken into account, industrial agriculture is at a disadvantage compared to organic farming.

In the case of energy crops, the GHG emissions released during crop cultivation and processing may negate the GHG neutrality of biofuels. It is possible that artificial fertilisers, with their nitrous oxide emissions, and machinery for harvesting, transport and processing, with their CO_2 emissions, could render the GHG savings from using biofuels over fossil fuels irrelevant in extreme cases (Lark *et al.* 2022). In addition to the problematic aspects we already described in Chapter 3.2.1, the energy balance – which is questionable in certain cases – is another reason for excluding biomass from energy crops from the scope of this study.

3.2.3. Principle 3: Protect and promote human rights and smallholder structures

In line with the SDGs, the economic and social development opportunities and risks for smallholders must also be taken into account; particularly as we are assessing biomass from countries in the Global South. As with the impacts on environmental protection and the climate, it is not possible to make general statements on the sustainability of individual types of biomass under this principle, as the social and economic impacts can vary significantly between regions and farming practices.

Criterion 1: Protect human rights and workplace safety

Growing crops that are suitable for use as biomass can give rise to social as well as environmental risks. If certain crops yield high harvests in a region, this can lead to illegal land grabbing. As a result, fertile land is no longer available to smallholders, who desperately need it for their survival. Working conditions can also be problematic on farmland that has not been seized through land grabbing. Other potential issues in

Box 7: Social impacts of oil palm cultivation

Conflicts over land use are frequently seen, particularly in rainforest areas, as a result of the lucrative oil palm cultivation. Typically, these conflicts arise between local communities, smallholders and palm oil companies (Abram *et al.* 2017). Indigenous peoples are particularly affected, as their ancestral land rights are often not recognised and their land is ceded to palm oil companies without their consent. Indigenous peoples and smallholders are often forced into natural forests, where they clear land for subsistence farming, resulting in iLUC. Furthermore, human rights violations such as forced and child labour, as well as the exploitation of workers, for example through wage dumping, also occur (Muhammad *et al.* 2019, Phung/Utlu 2020).

agriculture include a lack of, or inadequate, workplace safety measures, as well as child labour.

We therefore exclude biomass arising from farming practices that violate human rights, exploit rural communities or involve land grabbing.

Criterion 2: Create development opportunities for smallholders

The use of biomass gives smallholders the opportunity to increase their income. This helps to raise the standard of living of the rural population, which benefits disadvantaged groups such as women and indigenous peoples in particular. Due to their limited political influence, these groups have few other options for improving their situation. Furthermore, higher incomes make it possible to improve the efficiency of farming practices and make them more environmentally and socially compatible, for example in line with Good Agricultural Practices (GLOBALG.A.P. 2025).

Additional sources of income may encourage farmers to focus on individual profitable crops rather than diversifying their crops to promote biodiversity or cope with increasingly frequent extreme weather events. In extreme cases, this kind of one-sided agricultural structure can result in a complete crop failure and put significant pressure on remaining natural ecosystems. On the other hand, there is a risk that existing food production is displaced by cash crops. Although studies have shown that cash crops can increase farmers' incomes and thereby improve food security (Kuma *et al.* 2019), a failure of individual cash crops – for example, due to droughts or pest infestations – can exacerbate regional income and food crises (Achterbosch *et al.* 2014). In view of these considerations, we take into account only biomass that improves smallholders' incomes without creating economic dependency for them.

3.2.4. Principle 4: Prioritise biomass for food, soil improvement, materials and small-scale energy generation

The Sustainable Development Goals (SDGs) also include the efficient use of natural resources. Climate applications must be assessed to determine whether they are actually the best and most efficient use of biomass. When scarce, fertile land is used for growing crops, food security must be the priority. Some biomass from crop production plays an important role in livestock farming as feed or bedding. We also prioritise material uses, such as for soil improvement (e.g. mulch, compost) or as a building material, over energy uses. Using mulch helps to reduce the use of artificial fertilisers, and the CO_2 stored in the biomass remains sequestered in the building material for longer. Energy use should have the lowest priority, because the CO_2 stored in the plants is released immediately. Use as energy should only be prioritised if there is no higher-value use for the residues, and the primary nature of the biomass is unmistakably waste.

Criterion 1: Prioritise use as animal feed

Even when crop residues are no longer suitable for human consumption, they can still make excellent animal feed. Maize straw is an example of a biomass residue that is particularly suitable as animal feed, mainly for cows and sheep. Even though industrial meat production cannot generally be considered environmentally or socially compatible, it is acceptable to use the residues for animals provided that the crops are not grown primarily to produce animal feed. Use as animal feed is prioritised over energy use, not least to reduce the need for land to grow feed crops.

Criterion 2: Prioritise biomass for soil improvement and materials

If biomass is unsuitable as animal feed, it may prove more useful as a material than as an energy source. For soil protection, it is beneficial if some of the residues are left behind on the harvested field as mulch, incorporated into the soil or composted, so

Box 8: Application of the principles in a quantitative analysis

In the quantitative assessment, Principle 4 is expressed by the availability factor *Af*, while Principles 2 and 3, as well as the criterion "Protect biodiversity", are incorporated into the environmental and social compatibility factor *ESf*. We take the criterion "Exclude energy crops" into account as an additional factor corresponding to the share of production intended for human consumption.

that they can act as natural fertiliser, supplying the soil with organic carbon and nutrients. Mulch also protects soils from erosion caused by wind and rain. This is relevant, for example, in large parts of Africa, where nutrient deficiency is a major problem for agriculture (AUDA-NEPAD 2023). However, it is worth considering whether the biomass is not more effective as biochar than spreading the residues directly onto the fields. Other types of biomass, on the other hand, are suitable for building materials, such as sawdust as a raw material for chipboard or straw mixed with clay for construction. This ensures that the carbon remains sequestered in the long term.

Criterion 3: Prioritise optimal energy use

Biomass unsuitable for use as animal feed or as a material can be used in smallholder households to generate energy for cooking or heating. From a social perspective, using it as fuel is a better option because, compared to buying firewood, it is less expensive and, unlike fossil fuels, is carbon-neutral. Wood residues in particular are often used as fuel by the local population; introducing energy-efficient stoves brings significant benefits here (atmosfair 2024b).

3.3. Summary

The systematic application of the four principles “Prioritise land for food and biodiversity” (P1), “Climate change mitigation and environmental protection” (P2), “Protect and promote human rights and smallholder structures” (P3) and “Prioritise biomass for food, soil improvement, materials and small-scale energy production” (P4) reduces the total available biomass from residues to the actual share of usable biomass from residues. Its use in the production of electricity, bio-to-liquid kerosene or biochar does not impose any additional burden on people or the environment.

We have summarised the four principles along with their individual criteria in Table 3, together with a brief description. To clarify the links between these principles, Figure 5 shows how the total amount of biomass is further reduced when each individual criterion is applied, until ultimately only those biomass sources remain that are actually environmentally and socially compatible or available.

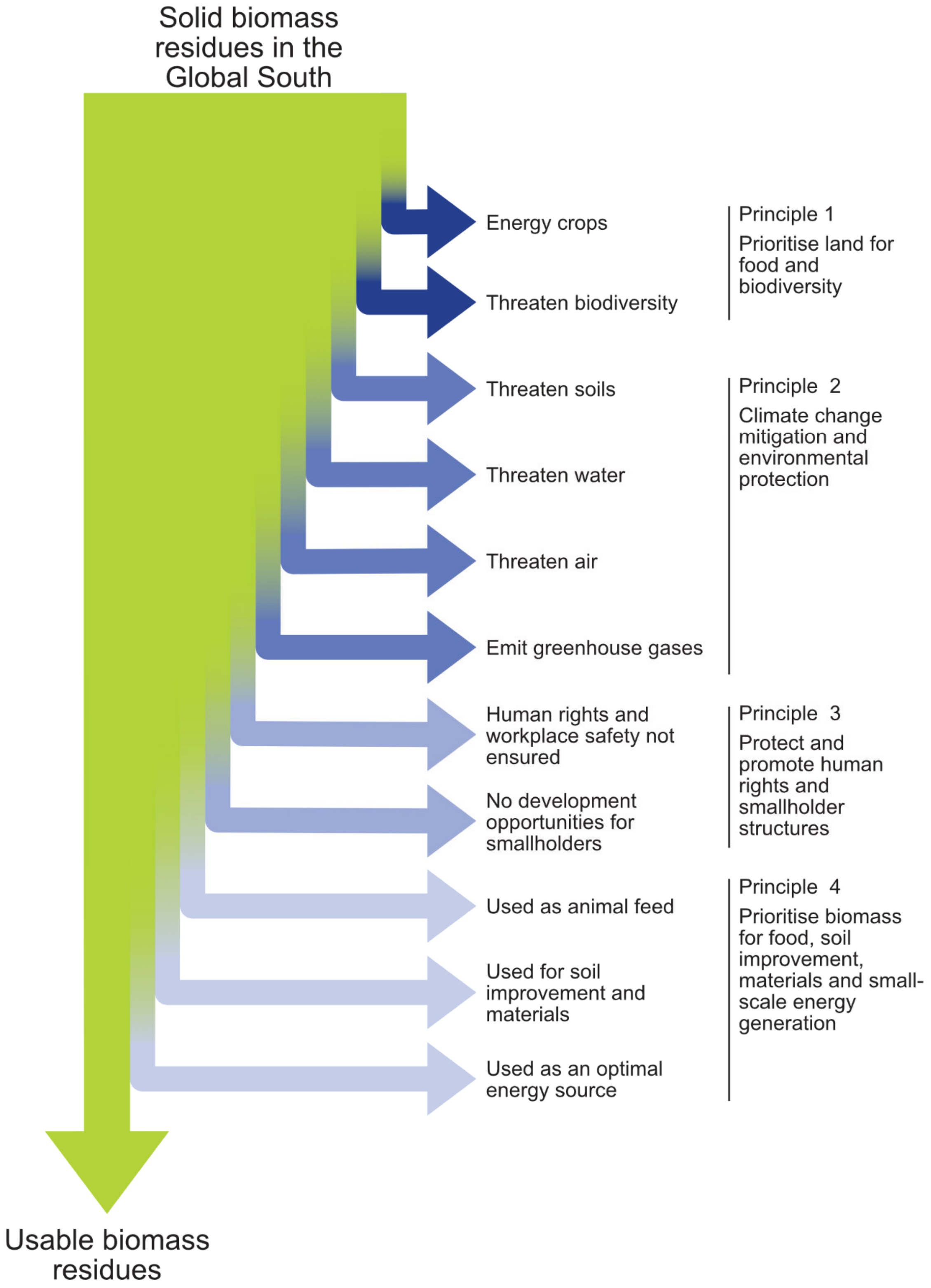

Figure 5: Diagram of step-by-step selection and links between the four principles

Table 3: Principles and criteria for the assessment of biomass

Principle	Criterion	Explanation	SDGs
Principle 1: Prioritise land for food and biodiversity	C1: Exclude energy crops	Crops used to produce biomass must not divert farmland away from food production, as is the case, for example, with energy crops grown for fuel production	2.1 – 2.2
	C2: Preserve biodiversity	Biomass must not originate from land that was previously home to high-value biotopes, or where farming has led to indirect land-use change (iLUC)	15.1 – 15.3, 15.5
Principle 2: Climate change mitigation and environmental protection	C1: Protect soil	Biomass from industrial agriculture must be carefully assessed, as it can be associated with nutrient loss, pesticide use and soil acidification; biomass from plants grown in ways that counteract land degradation should be viewed positively	2.4, 3.9, 15.1 – 15.3
	C2: Protect water	Biomass from industrial agriculture must be carefully assessed, as it can pollute freshwater through overfertilisation and the use of pesticides or lead to the overexploitation of water resources (unsustainable irrigation)	3.9, 6.3 – 6.4
	C3: Protect the air	Agricultural production should not pollute the air by burning crop residues or through slash-and-burn practices; if biomass is no longer burned thanks to BtL processing, this should be viewed as a positive development	3.9
	C4: Reduce greenhouse gases	Biomass from industrial agriculture must be carefully assessed, as it results in higher greenhouse gas emissions; residues from energy crops must be avoided	13
Principle 3: Protect and promote human rights and smallholder structures	C1: Protect human rights and workplace safety	Biomass should not stem from farming practices that violate human rights by leading to land grabbing or working conditions harmful to human health	2.3
	C2: Create development opportunities for smallholders	The use of biomass should improve smallholder income without creating incentives to switch from diversified food production to single, high-yield crops	2.3
Principle 4: Prioritise biomass for food, soil improvement, materials and small-scale energy generation	C1: Prioritise use as animal feed	Exclude biomass that can be used as animal feed	12.2
	C2: Prioritise biomass for soil improvement and materials	Exclude biomass suitable for soil improvement or as a building material	12.2
	C3: Prioritise optimal energy use	Exclude biomass that is already used as fuel by the local population	12.2

4. General suitability of different types of biomass from residues

This chapter applies the principles and criteria for environmental and social compatibility and availability set out in Chapter 3.2 to a qualitative analysis of various types of solid biomass. The aim is to provide guidance on which types of biomass are generally considered acceptable or problematic, and the criteria underlying these assessments, before we quantitatively determine the potential of environmentally and socially compatible and available biomass. Each type of biomass is assessed according to our criteria (Table 3) as follows:

- ①: Biomass is essentially environmentally and socially compatible, or its use actually contributes to greater sustainability.
- ②: Biomass is not environmentally and socially compatible depending on certain circumstances.
- ③: Biomass is mostly not environmentally and socially compatible.

Various literature sources are used here for the evaluation. If no evidence of potential risks can be found and none can be inferred theoretically, the relevant criterion is assigned a rating of ①. When compared globally, there are significant differences in farming practices, the degree of agricultural industrialisation and human rights violations. A detailed breakdown of these aspects at regional level would go beyond the scope of this study. For this reason, we rank the different types of biomass in such a way that the assessment applies to most residues in the Global South. Biomass with an overall rating of "mostly not environmentally and socially compatible" may therefore still be usable in specific cases. Table 4 summarises the individual and overall ratings of the various types of biomass. Detailed considerations on the individual types of biomass are outlined below.

In the quantitative analysis in Chapter 6, we treat almost all types of biomass equally, regardless of their qualitative assessment. When it comes to mostly problematic biomass that is used for human food, we take only this aspect into account to address the food vs. fuel dilemma. As there are no global production figures for sugar cane for human consumption, we exclude its residues entirely from the calculation. Even though there is data on the share of oil palm production for human consumption, we have opted not to calculate this potential in the interest of simplicity, as the environmental and social aspects of its cultivation are largely problematic and palm oil can be replaced by other vegetable oils in many applications (Noleppa/Cartsburg 2016, 9ff.).

4.1. Agricultural residues

4.1.1. Cotton

After synthetic fibres, cotton is the second most important source of textile fibres. While textile production is increasing around the world in line with rising population and income levels, the amount of land used for cotton production has stagnated since 1990, as the additional demand has been met primarily by synthetic fibres. Today, cotton is grown on 32 million hectares worldwide, or two per cent of total global cropland, and 25 million tonnes of the raw material are produced annually (FAOSTAT 2024). As the area of land devoted to agriculture has not expanded significantly for decades, no displacement effects at the expense of food production or ecosystems are discernible (P1).

Impacts of cotton production on people and the environment

There are significant differences in the conditions for growing and harvesting cotton: while many large-scale farms operate using highly mechanised methods, smallholders – particularly in the Global South – still rely on manual harvesting. The environmental impact of cotton production is relatively high compared to other crops.

Table 4: Evaluation of various types of biomass based on the principles and criteria from Chapter 3.2. The "Overall rating" column indicates whether the respective biomass is generally suitable for use (①), can only be considered environmentally and socially compatible to a limited extent (②) or is mostly problematic (③). If the biomass is rated lower than ① according to a maximum of two criteria, it is given an overall rating of ①. If the biomass is rated ② for at least three criteria, but no more than one criterion is rated ③, it receives an overall rating of ②. If the biomass is rated lower than ③ according to a maximum of two criteria, it is given an overall rating of ③.

	Principle 1: Prioritise land for food and biodiversity		Principle 2: Climate change mitigation and environmental protection				Principle 3: Protect and promote human rights and smallholder structures		Principle 4: Prioritise biomass for food, soil improvement, materials and small-scale energy generation			Overall rating
	C1	C2	C1	C2	C3	C4	C1	C2	C1	C2	C3	
Agricultural residues												
Cotton (stalks)	①	①	②	③	①	②	①	②	①	①	②	②
Cereal (straw)	①	①	②	②	①	②	①	①	②	②	①	②
Coffee (husks)	①	②	②	②	①	②	②	②	①	②	①	②
Cocoa (pods)	①	②	②	②	①	②	②	②	①	①	②	②
Maize (maize straw/maize	③	②	②	②	①	②	①	②	③	②	①	③
Cassava (stems)	①	①	②	①	①	①	①	①	①	①	②	①
Oil palm (berries/fibres/shells)	③	③	③	②	②	③	③	③	①	②	②	③
Rice (stalks/husks)	①	②	①	①	①	②	①	①	①	①	①	①
Nut crops (shells)	①	②	①	①	①	①	②	②	①	①	②	②
Soybeans (stalks/pods)	③	③	②	②	②	③	③	②	①	③	①	③
Sugar cane (bagasse)	③	③	②	②	②	②	②	②	①	①	②	③
Wood industry residues												
Sawmill by-products	①	②	②	②	①	①	①	①	①	②	②	②
Shrubwood	①	②	①	①	①	②	①	①	①	①	②	②
Wood harvesting residues	①	②	②	②	①	①	①	①	①	②	②	②
Others												
Sewage sludge	①	①	①	①	①	①	①	①	①	②	①	①

As already explained in Chapter 3.2.2, growers often use artificial irrigation to meet the plants' significant need for water. Depending on climate conditions, up to 20,000 litres of water are used to produce one kilogram of cotton (Paulitsch *et al.* 2004). However, the degree of artificial irrigation varies between different regions; half of all cotton fields worldwide are primarily irrigated by rain (Zhang *et al.* 2023). Cotton production can also have a negative impact on soil fertility if the period between harvesting and reseeding is so short that no catch crops can be planted. To compensate for this, large amounts of mineral fertiliser are used (Paulitsch *et al.* 2004), which is associated with greenhouse gas emissions like nitrous oxide.

Because monocultures tend to be infested by pests, cotton production accounts for over 10% of total global pesticide use, which contaminates the remaining freshwater resources (P2). Still, given its high export value, cotton farming also offers smallholders an opportunity to increase their income, which could be further boosted by selling crop residues for climate applications. However, many farmers are dependent on cotton, which leads to problems if crop failures occur. In India in particular – the world's largest cotton producer – smallholders lack adequate protection against these kinds of risks (Tirado 2010) (P3).

Usability of cotton stalks

After the harvest, woody stalks are left on fields and can be used for biomass; they are not suitable for improving soil quality or as animal feed. The only possible alternative use is as firewood, particularly in smallholder regions where fuel is scarce (P4). Otherwise, the residues are usually burnt on the fields, which contributes to emissions of GHGs and particulate matter (Yevich/Logan 2003, p. 4). An alternative use for electricity or BtL production, or as biochar, would improve air quality here (P2 C3). This means that cotton stalks – despite the environmental issues associated with industrial production methods in particular – appear to be a basically usable form of biomass, although the growing conditions must be assessed on a case-by-case basis to ensure they are environmentally and socially compatible.

4.1.2. Cereals

In this section, we discuss the suitability of wheat, rye, barley, oats, millet and sorghum for climate applications. Although these crops have different properties and growing regions, they should be viewed as similar in terms of the sustainability principles. Rice and maize are also cereals. However, their cultivation has its own specific characteristics and is discussed in separate sections.

After harvesting, straw is the main residue left over. Some of this straw can be used as animal feed; sorghum straw in particular is relatively nutritious for a residue and should be used exclusively for this purpose. Straw can generally be composted into humus or incorporated directly into the fields, where it acts as a natural fertiliser for the soil. In sub-Saharan Africa in particular, the large-scale harvesting of straw for energy purposes would pose a significant threat to soil fertility (Yevich/Logan 2003). This is particularly true of semi-arid and arid regions such as the Sahel zone south of the Sahara, where all straw residues should, where possible, be used as natural fertiliser (Yin *et al.* 2023) (P4).

Forms of cereal cultivation

Sorghum is also grown as an energy crop. However, this use should not be seen as the primary purpose of this cereal; its main purpose remains food production. Generally speaking, when cereals are grown, there is rarely any displacement at the expense of biodiversity (P1). Soil degradation caused by overuse of farmland can be minimised by using appropriate farming methods. However, industrial farming methods that pose risks to soil and water – such as the use of mineral fertilisers, pesticides, heavy machinery and the failure to rotate crops – are also used here (P2). In cereal cultivation, human rights violations such as land grabbing or child labour are relatively rare – in contrast to the cultivation of cash crops like cocoa or oil palms. The sale of straw, on the other hand, offers smallholders in particular the chance to boost their income (P3). Straw is therefore well-suited for climate applications, provided it is not required as a source of nutrients for the soil.

4.1.3. Coffee

Coffee is one of the most profitable cash crops. The expansion of global coffee production can, in some cases, contribute to the loss of forests and biodiversity; in Peru, for example, it is considered responsible for 25% of total deforestation. Globally, however, coffee plantations play a less significant role in deforestation than palm oil or soybean production, because they cover less land overall (Barreto Peixoto *et al.* 2023, 293). In environmentally sustainable coffee plantations, the coffee plants grow in the shade of larger trees, meaning these plantations are relatively rich in biodiversity (P1).

Alternative uses of coffee husks

Coffee husks are the outer shells that enclose the actual coffee bean and are removed during processing after the harvest. Coffee husks have limited nutritional value as animal feed and are sometimes used as a feed additive, but are primarily suitable as a substrate for growing edible mushrooms and for the production of certain beverages (Barreto Peixoto *et al.* 2023, 310) (P4). In terms of environmental impacts, monocultures are considered particularly problematic, even though they account for part of the coffee grown worldwide. Unlike traditional farming methods practised in the shade of larger trees, these crops are more exposed to sun and rain, leading to greater soil erosion (Barreto Peixoto *et al.* 2023, 293f.). Coffee monocultures also have lower CO_2 storage capacities than traditional plantations with additional larger trees. The use of artificial fertilisers and pesticides poses further risks to soil and water. One particularly critical aspect is the high volume of water used to separate the fruit pulp from the seeds, a process known as washing (P2) (Barreto Peixoto *et al.* 2023, 293f.). However, washing can be replaced by the "natural" process of drying the berries in the sun and then removing the pulp. Coffee produced naturally is generally considered to be more environmentally friendly.

Box 9: Child labour on cocoa plantations

Child labour is still widespread on cocoa plantations. In Ghana and Côte d'Ivoire, for example, around 1.5 million children work on cocoa farms (Hofmann, 2022). This not only keeps working children and young people from attending school, they are also exposed to massive health risks, such as accidents and pesticide contamination (Wildenberg/Sommeregger 2016).

Social impacts of coffee production

Even though coffee consumption – and with it, revenues from coffee beans – is rising worldwide, coffee producers often do not earn enough to finance a decent standard of living for themselves and their workers. This is because most value is added by processing companies and distributors. Hunger and a lack of access to healthcare and education are not uncommon in coffee-producing countries. Human rights violations such as child labour also occur in coffee production (Barreto Peixoto *et al.* 2023, 291f.). There are various fair trade initiatives that mitigate these negative social impacts. Consequently, some global coffee production can certainly be deemed acceptable in accordance with Principle 3: "Protect and promote human rights and smallholder structures" (P3). When it comes to coffee, a critical assessment is generally required to determine its environmental

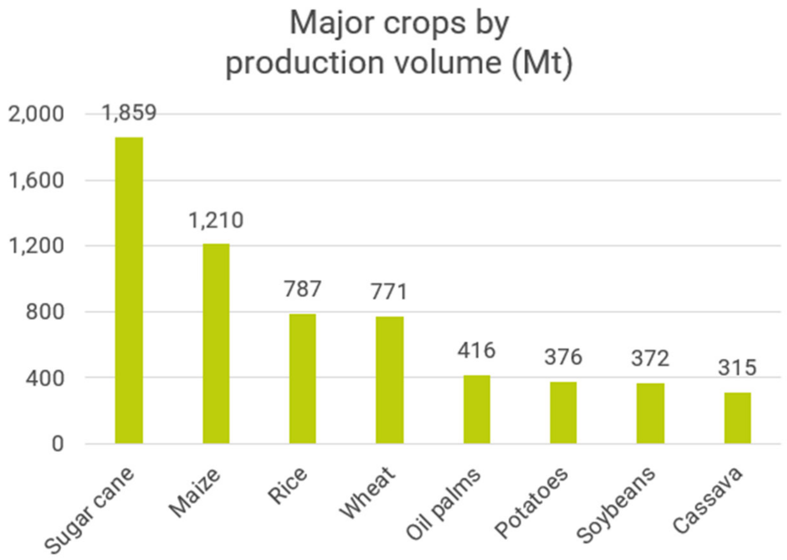

Figure 6: Major crops by production volume in 2021 (FAOSTAT 2024). The volume of sugar cane harvested refers to the cane harvested before pressing.

and social compatibility, which also applies to other plantation crops.

4.1.4. Cocoa

In cocoa production, empty pods – which contain the cocoa beans and constitute a large share of the total fruit mass – are left over as residues. Due to their high fibre and low protein content, these pods are of little use as animal feed and have only limited value as mulch; they usually rot on the plantations (Laconi/Jayanegara 2015, 344). Cocoa pods can therefore be used for climate applications that do not compete with other land uses (P4).

On the other hand, cocoa cultivation can have negative impacts on people and the environment. In West Africa in particular, many smallholders are financially dependent on cocoa cultivation. They earn less than 1.25 US dollars per day on average in this sector and thus live below the poverty line. Although cocoa is considered a lucrative cash crop, the revenues often do not reach the farmers themselves. However, as with coffee, there are more socially compatible farming practices that are promoted, for example, through fair trade initiatives (P3).

In the Ivory Coast, large monocultures have been established for cocoa cultivation since the 1960s, which has come at the expense of primary and secondary forests. An analysis of satellite imagery suggests that in this West African country, 37% of protected forest lost (or 360,000 hectares) between 2000 and 2020 can be attributed to cocoa plantations (Kalischek *et al.* 2022, 388). This has destroyed valuable biodiversity (P1). Furthermore, overly intensive agricultural use can degrade soil quality, and the use of highly toxic pesticides such as endosulfan poses health risks to farmers and causes significant environmental damage (P2) (Hofmann 2022, Wildenberg/Sommeregger 2016). However, as with coffee production, the potential social impacts of cocoa cultivation are more problematic than the environmental impacts. For this reason, the use of cocoa pod residues cannot be ruled out entirely, but requires a detailed and critical assessment of the specific situation.

4.1.5. Maize

Apart from sugar cane, maize is the only crop with a global annual production of over one billion tonnes (Fig. 6), meaning that large quantities of biomass are also available worldwide. Maize is also a very important energy crop, which is the main reason why maize production has risen steadily in recent years (Fig. 7). Bioethanol can be produced from maize starch, but the plant is also well-suited as a raw material for biogas production. As a result, maize is very often grown as an energy crop and is therefore not available as food. However, maize production for energy purposes not only competes directly with food production (Mitchell 2008) but may also pose an indirect threat to biodiversity if land previously used for food production replaces primary forests. Another problem is the fact that, at over 60%, the majority of maize production is used as animal feed[1] (Fig. 8). Given the dominant use of maize in inefficient meat production and as an energy crop, the global volume of maize residues cannot, for the most part, be considered environmentally and socially compatible, even though maize is also used as food for humans (P1).

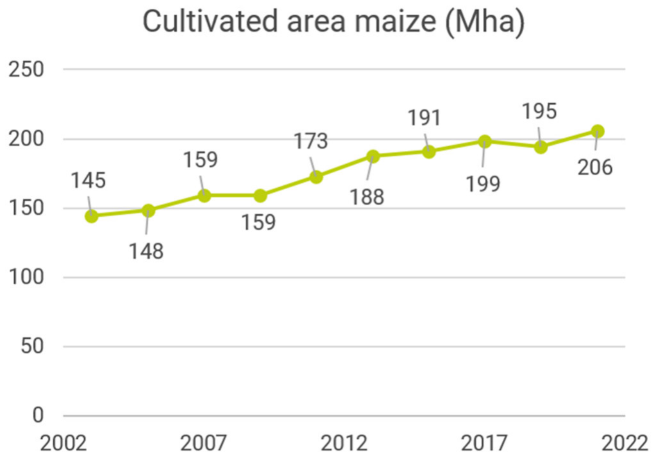

Figure 7: Increase in area for global maize production (FAOSTAT 2024)

Environmental risks of maize production

In maize production, too, the environmental risks depend on the specific farming method; particularly in large-scale monocultures, the use of fertilisers and

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[1] The use of the actual crop should not be confused with the use of the biomass. Although we view the use of biomass such as maize straw as animal feed positively, the cultivation of maize cereals for animal feed rather than human consumption is not compatible with our sustainability principles.

pesticides is harmful to the environment. In general, young maize is susceptible to erosion because it does not cover the spaces between the plants until late in the growing season, at which point the rows are fully closed. As a result, the soil remains exposed for longer and is thus at risk of wind and water erosion. In industrial maize cultivation, heavy agricultural machinery is often used, which compacts the soil, a practice that can increase the risk of both droughts and flooding (Nestler 2012). On the other hand, maize is well-suited to successive planting, which means that growing maize several times in a row leads to good yields (P2). As a lucrative energy crop, maize can at least generate additional income for the rural population, although there are also risks here due to financial dependence on monocultures (P3).

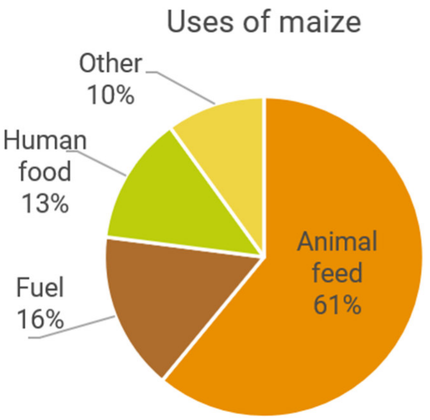

Figure 8: Uses of global maize production in 2021 (Serna 2022)

Alternative uses of biomass

After harvesting, maize straw is left over, consisting of leaves, plant stalks, maize cobs without kernels and husk leaves. Maize straw is well-suited as animal feed because it has one of the highest protein and energy contents among cereal straw types. Furthermore, it can also be used as a natural fertiliser to supply nutrients to the soil (Rusinamhodzi *et al.* 2015), or, due to its high starch content, for the production of bioplastics. When used for materials, the carbon previously removed from the air either remains sequestered or replaces artificial fertilisers and their associated GHG emissions (P4). Due to these higher-value alternative uses, maize straw cannot really be considered a waste residue. In addition to the well-known food vs. fuel dilemma, this is another reason why maize straw should only be considered partially suitable for the production of electricity, kerosene or biochar.

4.1.6. Cassava

Cassava is also called manioc. Its starchy root is a staple food in many countries of the Global South. After harvesting, woody stems are left on fields, but their residues cannot be used every year. Cassava is often grown as a biennial crop. Ten to 20% of the stems are used to propagate plants for the following season. They can also be processed into wood chips and used as mulch to prevent soil erosion. However, this practice is not widespread because the wood chips decompose very slowly (Zhu *et al.* 2015). Cassava farmers use the remaining stalks either as firewood or burn them right on the fields. In some cases, the residues also rot and go to waste, as is the case in Indonesia (Andini *et al.* 2016, 2f.). It is therefore more sustainable to use cassava residues for climate applications (P4).

Cassava plays no significant role in land conversion (P1) and most of the work involved in tilling the soil and tending the plants until the harvest is done manually. However, mineral fertilisers are used alongside organic ones, which can lead to GHG emissions (Le *et al.* 2013). Overall, however, emissions from cassava farming are lower than for other crops. Soil erosion is a greater concern, as large areas of soil are left exposed due to the slow growth of the plants and the wide spacing between individual plants (Howeler/Oates 2018). The environmental impacts of cassava farming can be considered low overall and can also be minimised using simple measures (P2), meaning that the use of this biomass offers smallholders additional development opportunities (P3). Due to their material properties, the lack of competing uses and generally favourable growing conditions, cassava stalks are a particularly suitable form of biomass.

4.1.7. Oil palms

Oil palms are the most important source of vegetable oil, followed by soybeans and rapeseed. To extract their fats for further processing, their fruits or kernels are pressed in mills, producing various residues. In addition to the empty fruit bunches and the palm pressed fibres left over from the fruit, the palm kernel shells are the most important biomass remaining after production. In addition, replanting generates up to 90 tonnes of dry matter from leaves and trunks per hectare (Awalludin *et al.* 2015). Some parts of the biomass – particularly leaf and wood cuttings – can generally be shredded and used as mulch. However, oil palms generate such large quantities of biomass (in Malaysia, for example, 83 megatonnes in 2012) that a considerable amount of material goes unused. However, this material is increasingly being used in biogas plants, which is an important alternative use to electricity, BtL and biochar production (P4).

Land-use conflicts

More than 80% of global palm oil production takes place in Malaysia and Indonesia. One particularly problematic aspect is that the cultivation of oil palms often involves the destruction of primary forest rich in biodiversity, which also leads to the loss of carbon sinks (Chapter 3.2.1). In the Malaysian part of Borneo, half of the oil palm plantations are located on land that was previously home to species-rich rainforest, and the other half on farmland and pastureland (Meijaard *et al.* 2020). Oil palms thus directly encroach on both land used for food production and biodiversity hotspots (dLUC). Palm oil is grown not only as an additive for the food industry, but also for the production of biodiesel or use in cosmetics. Although there are examples from Africa or South-East Asia where no deforestation took place for oil production (Vijay *et al.* 2016), competition for land use is a major problem from a global perspective (P1).

Environmental impacts of palm oil production

The social impacts of palm oil cultivation have already been addressed in Chapter 3.2.3. They are also predominantly negative due to land grabbing, child labour and wage dumping (Phung/Utlu 2020) (P3). In addition to land competition and socio-economic consequences, palm oil production is also problematic from an environmental perspective. Tropical soil generally has a low level of nutrients, which is further reduced by intensively managed plantations. To compensate for this, mineral fertilisers are often used on a large scale, which in turn are GHG-intensive and can lead to further soil acidification (Comte *et al.* 2013). The intensive use of fertilisers poses a risk of eutrophication to groundwater (P2).

Due to these various issues, we generally regard biomass from oil palms as unsuitable for climate applications. Still, it is important to note that these residues may be acceptable provided the plantation produces oil exclusively for human consumption and meets our criteria for environmental and social compatibility. Despite all these problems, oil palms are in fact the most efficient oil crop, yielding 3.3 tonnes of oil per hectare. Coconut palms yield only 0.7 tonnes and soybean plantations a mere 0.4 tonnes per hectare (Noleppa/Cartsburg 2016, 6). Switching to other oil crops could also lead to environmental problems because more land would be needed, even if the growing conditions were less problematic.

4.1.8. Rice

With annual production of over 780 million tonnes, rice is – after maize – the most widely grown cereal in the world for food (Fig. 6) and is a staple in many countries. There are essentially two different ways to grow rice: wet and dry cultivation.

Wet rice cultivation

In traditional wet cultivation, the roots of the rice plant are submerged in water or in waterlogged soil. The advantage here is that this method largely prevents pest and weed infestation, meaning fewer pesticides are needed. However, lack of oxygen leads to anaerobic digestion of the plant's organic matter and thus to the emission of the greenhouse gas methane (Adhya *et al.* 2014, 3ff.). 80% of rice production comes from wet cultivation, as yields are higher than in dry cultivation.

Wet cultivation generally causes hardly any soil erosion, and soil carbon content (SOC) is also 20% higher than in dry fields (Liu *et al.* 2021). Nutrients are better retained on terraces and can even be replenished by flowing water, meaning that nutrient loss and the use of artificial fertilisers are hardly an issue. Although rice production requires a great deal of water, rainfall and floodwaters can be efficiently harnessed using systems of canals and reservoirs to prevent freshwater resources from being overused (Arouna *et al.* 2023). If the rice plant residues are removed from the fields before they digest to become methane, GHG emissions can largely be prevented (P2).

Dry rice cultivation

Dry cultivation often takes place in drier upland areas where it is not possible to flood entire fields. However, a significant amount of water is still required here, leading to the use of limited freshwater reserves (Liu *et al.* 2011). This method of cultivation requires special varieties of rice that can tolerate a lack of water better, although yields are generally smaller than with wet cultivation. However, the benefit of reduced methane emissions is at least partially offset by the increased need for pesticides.

Dry cultivation is often the result of food production being displaced from lower-lying areas by more profitable cash crops. Some forests in upland areas are cleared using slash-and-burn practices to make way for rice cultivation, which can lead to a loss of biodiversity. The precarious situation of smallholders sometimes gives rise to land-use disputes (Ketterings *et al.* 1999). However, these phenomena are only relevant for a small share of global rice production, as wet cultivation is generally dominant (P1).

Benefits of rice straw and husks

Two types of residues are produced after harvesting: rice straw, which consists of the plant's stalks, and the husks, which enclose the rice grain and are separated in the rice mill. Rice straw and husks have little nutritional value, which is why they are not particularly suitable as animal feed or as organic fertiliser. They are therefore largely waste products, which is why the biomass is often burned or left to rot. However, the share of rice waste that is burned varies considerably among the countries: in Indonesia, as much as 80% of rice straw is used as feed or fertiliser (Andini *et al.* 2016), and in Thailand and Bangladesh too, burning rates are very low at less than 10%. Rice producers in Bangladesh, for example, often use rice husks as an energy source for rice mills (Ahiduzzaman 2007, 4). In Tanzania and Vietnam, by contrast, most of the residues are burned outdoors. In the middle of the range are countries like Nigeria and the Philippines, where around 30% of post-harvest crop residues are disposed of by burning (Omari *et al.* 2020, Pham 2016, Singh *et al.* 2021).

A Vietnamese study (Pham 2026) concludes that gasification in BtL plants is the most efficient use of rice waste, which is why this method should be prioritised (P4). If rice production residues are no longer burned on fields, which would improve air quality, this could help reduce the incidence of potentially fatal cancers and respiratory diseases. In India, rice straw accounts for 40% of all burned crop residues (Lan *et al.* 2022, Lin/Begho 2022). Using these residues could bring monetary benefits, particularly to smallholders (P3).

Overall, rice straw and husks are generally well-suited as biomass. The problems with rice are limited to potential methane emissions from wet rice cultivation, and forest displacement in dry cultivation. This would need to be assessed on a case-by-case basis in a separate study prior to use. The straw-like consistency of rice straw, in turn, can be particularly challenging for gasification.

4.1.9. Nut crops

The nut crops with the greatest potential for biomass are cashews, coconuts and peanuts. Despite differences in cultivation practices, they are similar in terms of the type and usability of their residues. After the actual fruit has been removed, all three crops leave behind woody shells that are unsuitable for use as animal feed or for soil fertilisation. The main competing use is for fuel, in the case of coconuts in the form of biochar, which is, however, often contaminated during production and varies greatly in quality (Zafar 2022). Otherwise, coconut residues often go unused and are discarded or burned, which impacts air quality and health (Obeng *et al.* 2020). This is why an alternative use for electricity or BtL production would make sense. Peanuts, however, can also be used as fertiliser (Witcombe/Tiemann 2022). Biomass from nut crops is largely a waste product with few alternative uses, which is the main argument in favour its use for climate change mitigation (P4). With regard to the other sustainability criteria, a more nuanced picture emerges depending on the crop.

Cashews

Cashews are a profitable cash crop and can increase a country's per capita income; West Africa is the most important region for growing these nuts. In Guinea-Bissau, for example, they account for nearly 90% of exports, with India being the main market (Seca *et al.* 2021, 386). However, this makes smallholders dependent on export markets, which is why crop failures can threaten their very existence. Working conditions in cashew production can also be problematic if the toxic outer shell of the cashew nuts is processed manually without adequate protective equipment like gloves (P3). On the other hand, fertilisers or pesticides are rarely used (P2) at least in the main producing countries in Africa, meaning that production conditions cannot be considered particularly harmful to the environment (World Bank 2022, 35f.). Due to the high profitability, cultivation sometimes takes place at the expense of primary forest and its ecosystems (Seca *et al.* 2021, 391f.). For this reason, the sustainability of cashew shells must be assessed on a case-by-case basis, even though environmentally friendly farming methods and the use of biomass for energy generation are generally possible (P1).

Coconuts

Coconut cultivation takes place mainly in Indonesia, the Philippines, India and Brazil. The labour involved in harvesting coconuts is quite high, as climbers must pick the fruits one by one from the tops of the tall trees. This means there are no large-scale mechanised plantations, which is why coconut cultivation is generally less problematic from an environmental perspective than other crops. Most of the production is carried out by smallholders; in Indonesia, 50% of farmers own coconut plantations of three to four hectares and only two per cent owns more than five hectares (Mawari/Ersilya 2023, 39ff.). Consistent with the principle of “Climate change mitigation and environmental protection”, coconut husks can certainly be considered environmentally and socially compatible biomass (P2). Human rights violations such as child labour also take place in coconut cultivation, as evidenced, for example, in the Philippines (HAUMAN 2021). However, there are at least fewer documented cases of child labour in coconut cultivation (P3). There are no known cases of large-scale displacement of biodiversity areas due to coconut cultivation (P1).

Peanuts

In addition to the USA and China, the main peanut-producing countries are India, Nigeria and Senegal. As nutritious and protein-rich oilseeds, they are an important foodstuff in many growing regions. Peanuts are often grown in subsistence farming in the Global South, with the sale of the shells potentially providing smallholders with additional income (P3). There are various farming methods, ranging from year-round to seasonal harvest cycles and from monocultures to mixed cropping. Some areas are irrigated artificially, but rainwater is the main source of irrigation (Talawar 2004). As a catch crop, the peanut can enrich soils with nitrogen, thereby replacing mineral fertilisers. However, there is a risk of soil degradation if the plants are spaced far apart (Witcombe/Tiemann 2022) (P2).

Due to their woody consistency and limited number of competing uses, nut shells are generally well-suited for climate applications. Different types of nuts are mainly grown as food for humans, making the “food vs fuel” dilemma is a non-issue. However, it is important to ensure that plantations are not established at the expense of primary forests, and that human rights violations do not occur there.

4.1.10. Soybeans

Soybeans are an important crop, both in terms of production and trade volume. Between 1997 and 2017, global production doubled from 144 to 353 million tonnes (Leuba 2019, 8), while the area under cultivation has increased from 80 to 130 million hectares over the last 20 years (Fig. 9). Three-quarters of soybean production is used as animal feed, the remainder as protein for human consumption, and a small share as a raw material for biofuels (Fig. 10). Consequently, most uses are in direct conflict with (more efficient) food production; the use of soybeans as animal feed does not meet established sustainability criteria. In Brazil, the country with the highest production volume,

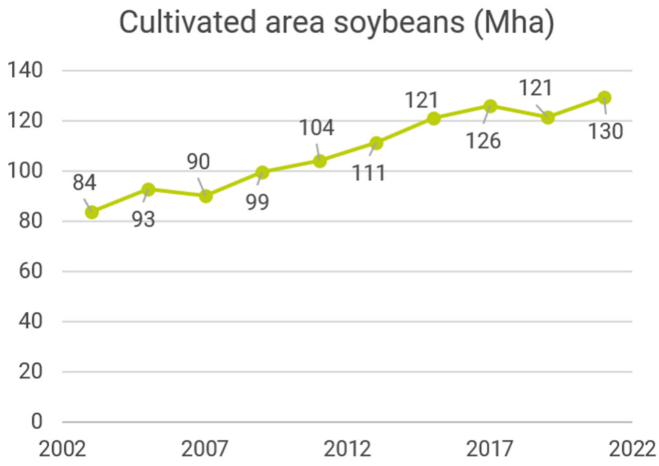

Figure 9: Increase in global soybean cropland (FAOSTAT 2024)

soybeans are often grown in the humid savannah of the Cerrado region, where they destroy valuable ecosystems. The damage is even worse in the Amazon, where primary forests rich in biodiversity are being cleared for soybean plantations (Fearnside 2001, Leuba 2019). Between 2000 and 2019, the amount of land used for soybean plantations in the Amazon region increased tenfold, from 0.4 to 4.6 million hectares (Song *et al.* 2021). Because soybeans compete with food production and threaten biodiversity, their biomass can largely be considered environmentally and socially incompatible (P1).

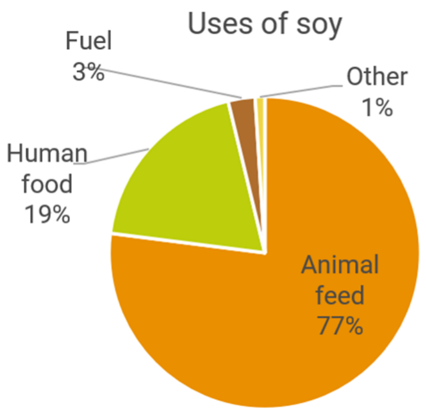

Figure 10: Uses of global soybean production 2017-2019 (Ritchie 2024)

Use of residues and growing conditions for soybean crops

Soybean crop residues consist of the straw and the pods that contain the beans. Soybean straw used as animal feed has a lower nutritional value than cereal or maize straw. However, a large part of the harvest residues should remain on fields to replenish the soil with nutrients (Rees *et al.* 2018), which is particularly important on tropical soils that are generally nutrient-poor (P4). Soybeans can extract nitrogen from the air and thus grow even on nutrient-poor soils. For this reason, soybeans often grown on overgrazed pastureland where rainforest has previously been cleared. The environmental costs of soybean cultivation are generally high, as it is usually grown in industrial monoculture on intensively farmed land with the heavy use of pesticides, lime and agricultural machinery. Furthermore, slash-and-burn practices to clear forests leads to significant emissions of pollutants and CO_2 (Escobar *et al.* 2020, Leuba 2019). The soil is heavily tilled for soybean cultivation, as there is often a short crop rotation cycle. The exposed soil between the plants and the heavy use of agrochemicals lead to soil degradation (Then *et al.* 2018, Vitali 2011) (P2).

Particularly in the Amazon region and the Cerrado in Brazil, there are serious conflicts between agribusinesses in the soybean industry and the local smallholder population. Land is often illegally “grabbed” for soybean cultivation, and previous users have been displaced, often including indigenous groups. Due to the high degree of mechanisation, soybean plantations create few jobs for the local community, meaning that at best they can only share indirectly in the profits of the plantations where they previously practised subsistence farming (Leuba 2019, Miersch 2018) (P3). The use of biomass from soybean production therefore generally runs counter to all four sustainability principles, even though the share of production that serves directly as food for humans is generally acceptable.

4.1.11. Sugar cane

With annual production of nearly two billion tonnes, sugar cane is the world’s most widely grown crop (Fig. 6).[1] Once the sugar cane has been harvested and the juice extracted, large quantities of fibrous residue remain, known as bagasse. This material cannot be used either as animal feed or as fertiliser, which is why it is only suitable for energy production. Sugar mills often use the bagasse themselves to meet up to 30% of their energy requirements. The rest of the bagasse is usually simply burned outdoors (Andini *et al.* 2016, Omari *et al.* 2020), meaning this share of biomass could be made available for use in BtL plants (P4).

Sugar cane as a source of bioethanol

Sugar cane is used largely as an energy crop. When processed into bioethanol, it plays an important role in the transport sector, particularly in emerging economies like Brazil and India. In these main growing countries, sugar production cannot be separated from ethanol production; both sugar and

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[1] The FAO collects data on the total weight of the harvested sugar cane before the sugar juice is extracted.

ethanol are generally extracted from the plant's juice (Ferreira-Leitão *et al.* 2010, 66). Whether sugar mills focus their production on food additives or fuel depends on price trends on the commodities market (Wright 2021). For this reason, it is not possible to specify a precise share of sugar cane production that is intended exclusively for human consumption rather than as an energy crop, unlike with maize and soybeans. When used as an energy source, sugar cane can displace food crops both directly and indirectly, or destroy biodiversity areas. In the Cerrado savannah in south-western Brazil, for example, the area of cropland expanded significantly between 2006 and 2013. Each additional hectare of sugar cane displaced 0.14 hectares of natural vegetation and 0.47 hectares of pastureland (Ferreira Filho/Horridge 2014). Furthermore, indirect land-use changes (iLUC) can be seen when sugar cultivation pushes livestock pastures and soybean fields into rainforest areas (Box 5, Chapter 3.2.1). Sugar cane residues can only be considered environmentally and socially compatible if there is no link to ethanol production (P1).

Economic impacts of sugar production

The sugar and bioethanol industry has contributed to positive economic development, particularly in Brazil (Moraes *et al.* 2015). For instance, compared to land used as pasture, sugar cane production increases income and economic output. However, this high profitability also leads to corruption and land grabbing, which is often carried out using armed force. However, these problems only occur in certain countries and regions (e.g. in Cambodia or the state of Pernambuco in Brazil), whereas they do not arise in other sugar-growing areas (e.g. in Thailand or the state of São Paulo in Brazil), which is why no general statements can be made about this issue (Pred 2013, Falck 2015). The socio-economic impacts of sugar cane production thus vary regionally and can range from acceptable to unacceptable (P3).

When land is in short supply, sugar cane production intensifies, resulting in higher environmental costs due to soil degradation and groundwater pollution, as more agricultural machinery, fertilisers and pesticides are used (Hunke *et al.* 2015). In some countries, like Thailand, it is still common practice to burn weeds and drive away mosquitoes before the harvest to make harvesting easier. This practice pollutes the air with particulate matter (P2). For these reasons, and above all due to the food vs. fuel dilemma, bagasse cannot in many cases be considered environmentally and socially compatible biomass, despite the large quantities available. In some cases, however, it can certainly be used, for example where it is grown solely for food production.

4.2. Wood industry residues

The following discussion does not include waste wood. Although it is also a residue that could potentially be used, there is very little data on its international availability (European Commission *et al.* 2016), which is why these quantities cannot be estimated and are not taken into account in this study.

4.2.1. Sawmill by-products

When cut tree trunks (roundwood) are processed in sawmills or plywood panels are produced, sawmill by-products are created. These consist of larger wood chips and finer sawdust.[1] The latter, in particular, can be compressed for use in the production of fibreboard or chipboard. This use is preferential to its use as energy, as the carbon remains sequestered in the material and fewer logs need to be removed from the forest. It is also conceivable that the local population could use larger wood chips directly as fuel, which would eliminate the need for fossil fuels. However, particularly in the Global South, sawmill by-products are either dumped in bodies of water or burned along roadsides (Onochie *et al.* 2018). These unused quantities offer potential for climate applications. Above all, kerosene production generally adds more value than its direct use as firewood (P4). However, the need for firewood in smallholder households must be taken into account. One possible reason for the low level of use of sawmill by-products is the lack of adequate transport and logistics infrastructure, which cannot meet any potential local demand.

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[1] The production of fibreboard and chipboard also generates waste, in the form of sanding dust and fine wood particles. These account for around 10% of the total amount of timber used and are also included in our analysis.

Criteria for environmentally compatible forestry

When used as a building material, the carbon footprint of timber is generally better than cement. Timber in buildings stores CO_2 in the long term, whereas cement production emits large quantities of CO_2 (WBGU 2020, 223ff.). However, not all sawmill by-products are considered suitable for use according to our principles. Illegally harvested timber from species-rich primeval forests is just the most obvious source of raw material that has to be excluded to ensure environmental compatibility. Illegal logging of this kind occurs, for example, in the context of iLUC, which is caused when the cultivation of energy crops is expanded (see Chapter 3.2.1). Although the Programme for the Endorsement of Forest Certification Schemes (PEFC) and the Forest Stewardship Council (FSC) have labels that are recognised globally to help assess the environmental compatibility of legally harvested timber, the latter organisation in particular has attracted criticism because, in some cases, it does not ensure sufficient protection for intact ecosystems and certifies timber from primary forests (Engert *et al.* 2023, Greenpeace International 2021, 84ff.). We do not consider FSC or PEFC certification of a forest to be adequate to guarantee the environmental compatibility of the wood.

From atmosfair's perspective, the suitability of wood residues for climate applications depends on the type of forest (P1). The following forest types are listed in descending order of their ecological value, although it is important to note that not all forests with a particular value are equally protected:

- We do not consider timber from nature reserves classified under categories Ia to IV of the International Union for Conservation of Nature (IUCN; Day *et al.* 2019, 2) to be environmentally compatible. An exception exists where harvesting timber helps to preserve the ecosystem, such as when creating firebreaks.
- We also consider timber from high-biodiversity primary forests that do not have official protected area status to be unsuitable – with the exception of timber that is harvested as part of conservation measures.
- In the case of forests in areas classified under IUCN Categories V (protected landscape or seascape) and VI (protected area with sustainable use of natural resources), the use of residues is acceptable provided that management does not jeopardise the conservation of these protected areas.
- Even without official protected status, near-natural commercial forests are more biodiverse than monocultures. This biodiversity must be preserved during timber production so that the timber can be classified as environmentally compatible.
- Timber plantations are established specifically for commercial management and tend to be monocultures with generally low levels of biodiversity. This is particularly problematic when they displace more species-rich ecosystems such as primary forests (Bremer/Farley 2010, 3899ff.). In the forestry sector of the Global South, industrial tree plantations are on the rise, where timber production is maximised through the intensive use of water and fertiliser (Overbeek *et al.* 2012, 30ff.). Fast-growing trees like eucalyptus can significantly impact the natural water cycle even without artificial irrigation (Alvarez-Garreton *et al.* 2019). That is why atmosfair imposes the following requirements on plantations that supply the timber that ultimately produce the sawmill waste used for climate applications:
    - The timber plantation must not be expanded at the expense of surrounding primary forest or other natural ecosystems (P1).
    - The plantation must not have been established in place of high-value primary forests or other natural ecosystems with high biodiversity (P1).
    - Despite commercial use, plantation operators must maintain a minimum level of biodiversity in the forests, for example through unused biotope islands and deadwood left in the forest (P1).
    - Plantation operations must not lower the water table, which can occur as a result of both intensive artificial irrigation and the high water consumption of certain trees alone (P2).
    - Overfertilisation of the soil, which leads to acidification and GHG emissions, must be prevented (P2).

In practice, it is necessary to assess individual timber operations and the raw materials they use in separate case studies. This study can only provide a rough estimate of the quantities of usable sawmill by-products that are generally available. Limiting the scope to sawmill by-products, in turn, ensures that the plantations are primarily operated for the production of sawn timber and not for the use of whole trees, as in the paper or pulp industry.

In contrast to illegal logging in protected forests, land grabbing is rarely found in forestry and occurs mainly in the industrial plantations mentioned above (Overbeek *et al.* 2012, 63f.). However, inadequate safety measures or a lack of social protection can be a problem, particularly for seasonal workers. A large part of forestry work takes place informally (FAO *et al.* 2023, 1ff.). A new use for sawmill by-products could offer the rural population additional sources of income (P3).

4.2.2. Shrubwood from the restoration of grass savannahs

Since the end of the 19th century, shrubwood is been spreading in grass-dominated savannah systems, a phenomenon known as “bush encroachment” (BE). One reason is overgrazing of savannahs, which can destroy the grass layer, allowing shrubs to take over from grasses. The increased CO_2 levels in the atmosphere encourage this process, as does the absence of shrub-eating wildlife. Dry and warm temperatures enable shrubs to metabolise carbon from the air more quickly than grasses, giving them a competitive advantage within the ecosystem. In Namibia, for instance, savannah landscapes that were once dominated by grass have been completely overtaken by shrubwood (O’Connor *et al.* 2014). As a result, people in regions affected by bush encroachment have fewer grazing areas available (Kyriakarakos *et al.* 2023, 21ff.).

For this reason, shrubwood growing on the land is often removed and could potentially be used for climate applications. There is no higher-value alternative use, as the cleared shrubwood is not suitable as animal feed or for material use (P4). The environmental impact of clearing shrubwood to restore grass savannahs, however, is somewhat controversial. Even though this provides the local population with more grazing land (P3), from a climate change perspective it is beneficial to leave at least part of the shrub cover intact. Shrubs store significantly more CO_2 in their biomass than grass. Furthermore, shrub vegetation has a positive effect on how much carbon soils can store (P2) (Schick/Ibisch 2021, 11f.). As woody vegetation continues to spread, a dry forest ecosystem may develop in the long term, which has even greater potential for CO_2 storage.

Biodiversity and bush encroachment

Biodiversity in savannahs appears to be at its highest when 20% to 40% of the land is covered by bushy vegetation, specifically when grass and shrubs coexist (thus allowing, at least in part, the natural progression towards dry forest). Insects and smaller predators in particular can use shrub vegetation as a habitat. Further bush encroachment, however, threatens the ecosystem living in the grass layer, such as reptiles and rodents (Dreber/Blaum 2016, 212f.). For the best possible protection of biodiversity, only the use of shrubwood from areas that have been only partially cleared is suitable (P1). To strike a balance between biodiversity and the need for grazing land, it seems generally acceptable for 80% or even more of the land to be cleared of shrubwood (P3). Because savannah shrubs regrow even after being cleared, it is possible to harvest large quantities of biomass over long periods without completely clearing the savannah of shrubs (Kyriakarakos *et al.* 2023, 23f.). Provided that clearing shrubwood meets biodiversity requirements, it constitutes environmentally and socially compatible biomass.

4.2.3. Wood harvesting residues

Wood harvesting residues are the parts of vegetation left behind after trees have been felled. These consist primarily of sawn-off branches and trunks that cannot be reused in sawmills. These residues are often burned after the trees have been cut down to make way for new growth. As there is no competing use, these residues can certainly be used for climate applications. However, if some of the residues are needed to supply nutrients to the soil, they should not be completely removed (P4). The same environmental and social criteria apply to the forests where the wood harvesting residues originate as to the forests from which sawmill by-product timber comes (P1, P2, P3 in Chapter 4.2.1).

4.3. Sewage sludge

Sewage sludge is produced in wastewater treatment plants when solid components are filtered out of wastewater or separated by other technical processes. It consists largely of organic substances and, in its dried form, is generally suitable for the same climate applications as agricultural and wood residues. It is even possible to convert it to biochar by means of pyrolysis. For wet sewage sludge, there are other energy uses that also help to mitigate climate change (Blagojević *et al.* 2021, p. 306ff.):

- Biogas production by anaerobic digestion
- Indirect electricity generation using combustion and gas turbines
- Direct electricity generation in microbial fuel cells

However, it is important to note that combustion can produce harmful exhaust gases and that microbial fuel cell technology is not yet fully developed. For this reason, the use of sludge for energy generation in biogas plants should be regarded as a particularly relevant alternative to drying followed by combustion or gasification. This is especially true when no exhaust heat is available for drying the sludge.

Essentially, sewage sludge is a waste material that is technically difficult to dispose of safely for the environment, as it may contain toxic heavy metals as well as organic pollutants. Due to its nitrogen and phosphorus content, it can generally be used as a fertiliser, which is the case particularly in the Global South, but also in industrialised countries. While the use of sewage sludge on fields in Europe is strictly regulated and the prior removal of toxins is mandatory (Bachmann 2015, 7f.), there are often no such regulations in the Global South (Wiśniowska *et al.* 2019, 215ff.). Under these circumstances, it can only be considered environmentally and socially compatible if the sewage sludge is used for energy purposes and does not enter the environment, not even as fertiliser on fields (P2). Provided that the sewage sludge is adequately treated to remove pollutants, however, it makes more sense to use it as fertiliser on fields. A case-by-case assessment is needed here (P4). As global phosphorus reserves are limited, this valuable element should definitely be removed from the sewage sludge before it is dried and gasified or combusted (Box 10).

Box 10: Recovery of phosphorus from sewage sludge

In addition to organic substances and heavy metals, sewage sludge also contains valuable nutrients such as nitrogen and phosphorus. As phosphates are suitable for use as fertilisers and occur only in certain parts of the world, phosphorus should be extracted from sewage sludge prior to its use for energy generation. Technical processes already exist for this purpose, which are set to be rolled out nationwide in Germany by 2030 (Schaum *et al.* 2020). However, these processes increase the treatment costs for sewage sludge. The revenues from the phosphorus recovered this way cannot compete with the prices of primary raw phosphate as long as global phosphorus reserves have not yet been exhausted.

The use of sewage sludge varies between countries with different legislation, even within the European Union (Blagojević *et al.* 2021, p. 308). In Latin America, Africa and Asia, sewage sludge is primarily used as fertiliser in agriculture and is rarely used in biogas plants (Wiśniowska *et al.* 2019, 215ff.). However, only patchy data on this is available (Hanum *et al.* 2019, 4).

Sewage disposal in the Global South

The share of wastewater treated in wastewater treatment plants that yields sewage sludge varies greatly from country to country and depends mainly on how developed the country's infrastructure is. Globally, an estimated 52% of all wastewater is treated (Jones *et al.* 2021), producing sewage sludge that can be used for energy generation. In countries where there are no comprehensive sewage systems, faecal matter is often collected in tanks or septic tanks and does not end up in a sewage system at all. In some cases, this faecal sludge is used as fertiliser in agriculture, despite the toxic substances or pathogens it contains (Wiśniowska *et al.* 2019, 217). In some countries in sub-Saharan Africa, pilot projects are already underway that use faecal sludge from septic tanks for energy generation in biogas plants (UNEP 2020).

However, estimating these potential quantities is much more difficult than estimating the volume of sewage sludge from treated wastewater, which is why we do not take them into account in this study.

Box 11: Individual assessment of each residue

The aim of this study is to estimate the global potential of biomass, which is why it makes some generalisations regarding the environmental and social compatibility of certain types of biomass. In practice, however, each case should always be considered individually to determine whether specific residues meet the criteria for sustainable kerosene production. Our table (Table 4), which sets out the individual criteria, can be used as a checklist for this purpose. It is possible that certain residues, which may be classified as environmentally and socially incompatible, or are predominantly regarded as such, may in individual cases yield environmentally and socially compatible, usable biomass.

5. Data sources used

To estimate the potential of genuine biomass in the Global South, we developed a quantitative framework where each row of the table represents a specific crop, timber species or treated wastewater in a particular country. This could be, for example, "rice in India", "hardwood in Colombia" or "treated wastewater in South Africa". To determine the potential volume of residues in each row, we used the following sources:

1. We took the **production volumes** of crops and wood products in the countries in question from the Food and Agriculture Organization of the United Nations database (FAOSTAT 2024), the quantity of shrubwood from a case study for Namibia and for South Africa (Stafford *et al.* 2017), and the volume of treated wastewater per country from a global study that arrives at an estimate using regression analysis (Jones *et al.* 2021). In contrast to timber production, no statistics are available for the global volume of timber harvest residues, so we do not include this residue type in the quantitative analysis.
2. **RPR values and moisture content** for the individual crops and wood products, which are used to calculate the quantity of dry biomass, can be found in various literature sources. This applies to both agricultural and sawmill residues (e.g. Koopmans/Koppejan 1997, Ojolo *et al.* 2012, Yevich/Logan, 2003).[1] To calculate the volume of sewage sludge generated during wastewater treatment, we use the median value for European Union countries where detailed data is available (Eurostat 2023, FAO 2024).
3. We obtain the **environmental and social compatibility factor *ESf*** for 33 rows from our interviews and can apply these values to another 107 rows.[2] We derive the *ESf* for all other rows from the Sustainable Agriculture Matrix (Zhang *et al.* 2021), which is currently the only available study quantifying sustainable agriculture at a global level.[3] Both the data from the interviews and the data from Zhang *et al.* (2021) primarily relates to environmental aspects, as social and economic aspects are difficult to quantify. However, we assume there is a correlation between the environmental and social aspects of sustainability. To determine the environmentally and socially compatible volume of wood residues, we use the percentage of a country's total timber production that is not harvested illegally (World Bank 2019, 43).
4. We can also determine the **availability factor *Af*** for 33 rows using interviews. The *Af* for a further 153 rows can be derived from specific literature sources that indicate the share of combusted or unused biomass for individual countries.[4] It should be noted that in a country with a known combustion rate, biomass that is not combusted may well go unused and be available. The combustion rate therefore underestimates the quantity that is actually usable. Where no specific literature can be found, we use a general percentage of agricultural waste that is burned in the individual regions of the world (Rogner 2012, 479). For the availability of wood residues, we subtract the quantity that could be recycled in a country's particleboard production from the total amount of residues.[5]

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[1] Where there are discrepancies between the various sources, we take the value that is identical in at least two sources, or the lowest value where the figures differ across the board.

[2] A country's *ESf* for a particular crop can only be applied to the same crop in other countries if those countries are located in the same geographical region and, according to Zhang *et al.* 2021, generally exhibit a similar level of sustainability.

[3] To evaluate the SDG target of expanding sustainable agriculture by 2030, the FAO developed a methodological framework (FAO 2018). However, at the time of this study, data collected in accordance with these principles is only fully available for the European Union.

[4] Based on Zoma/Sawadogo 2023 and Obeng *et al.* 2020, we assume that there are generally no higher-priority alternative uses for cashew and coconut shells, which is why we estimate a Vf = 1 for all countries here.

[5] We derive the percentage of chipboard and fibreboard material that is recycled from wood residues from European

To assess the environmental and social compatibility of biomass, we apply an additional factor for maize and soybean production: The proportion of production used as food for humans (Chapter 4.1.5, 4.1.10). Only this percentage conforms to the principles of our study; we do not include the production of animal feed or energy crops because it competes with land used for human food production. As there are no constant numbers for the energy production from sugar cane available, and as palm oil should be replaced by other vegetable oils in many food industry uses due to its significant problems, we exclude these crops entirely from the volume estimate and setting the factor to 0.

With regard to availability, an additional factor for cereal straw in semi-arid and arid regions is also applied to certain rows. As mentioned in Chapter 4.1.2, straw is particularly valuable as a natural fertiliser in dry areas. For this reason, we exclude cereal residues entirely from our potential estimate in arid regions and by half in semi-arid regions.[1]

Box 12: Illegal logging in Nigeria

A total of 87% of logging in Nigeria is carried out illegally (World Bank 2019, 43). This is particularly problematic given that the tree cover in the north of the country acts as a significant natural barrier against the spread of the Sahara Desert. One reason why trees are cut down is for firewood. To help people use less firewood, atmosfair supports the production and distribution of Save 80 stoves, which require only 20% of the firewood previously needed for cooking.

Union statistics (Reichenbach *et al.* 2016, 260). In countries of the Global South, this percentage is likely to be lower rather than higher, meaning that we are also likely to underestimate the available quantity here.

[1] The percentages of semi-arid and arid areas for each country are taken from UNEP-WCMC (2007). In the interest of simplicity, we assumed an even spatial distribution of agricultural production across the respective countries. As agriculture is concentrated primarily in wetter regions, our approach yields a lower residual quantity than is actually available, which is in line with the principle of conservative estimation.

6. Results: Usable quantities of genuine biomass

In Chapter 3, we derived criteria for determining the environmental and social compatibility and availability of solid biomass. In Chapter 4, we applied these to various types of solid biomass using a qualitative analysis to determine the extent to which these types of residues generally meet our criteria. We also take almost all of these residue types into account in the following quantitative analysis, where we calculate the quantities of generally acceptable residues available in the countries of the Global South. We completely exclude waste from oil palms and sugar cane entirely due to the fuel vs. food conflict and a lack of information on the share of production used for human food.

6.1. Agricultural residues

The quantities presented in this chapter relate to solid agricultural residues that meet our criteria and are suitable for electricity generation, BtL production or biochar production. Their economic potential is discussed in Chapter 7.

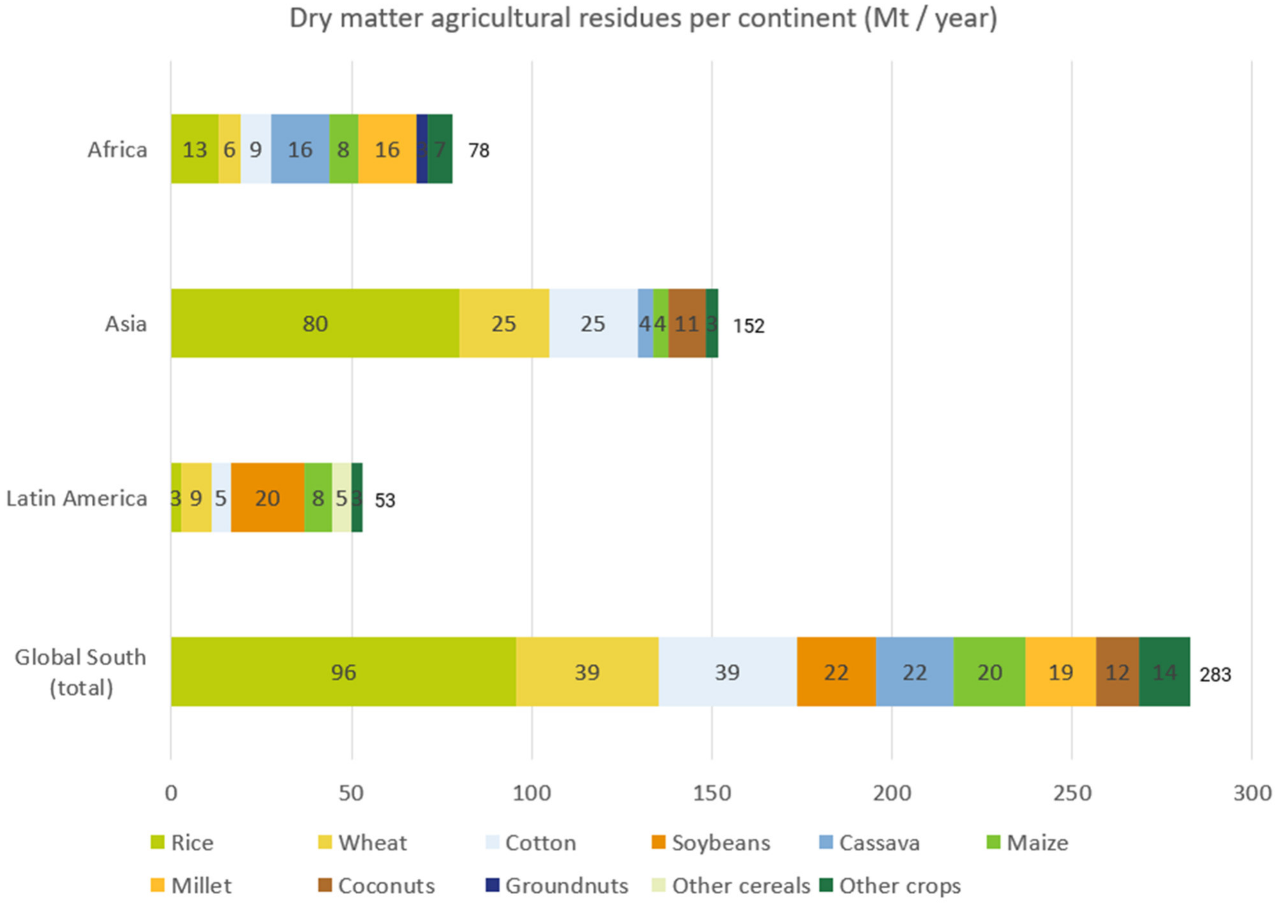

Figure 11: Annual dry matter yield of environmentally and socially compatible and available agricultural residues by crop type and continent.

Table 5: The most abundant environmentally and socially compatible and available biomass in the three most populous countries on each continent.

Continent	Country	Largest annual volume of biomass	Second-largest annual volume of biomass	Third-largest annual volume of biomass
Latin America	Brazil	11 million tonnes of soybean pods and straw	3.4 million tonnes of cotton stalks	1.9 million tonnes of maize straw
	Mexico	1 million tonnes of maize straw	687,000 tonnes of millet straw	679,000 tonnes of cotton stalks
	Colombia	117,000 tonnes of rice straw and husks	70,000 tonnes of maize straw	70,000 tonnes of coffee husks
Africa	Nigeria	2.6 million tonnes of millet straw	1.7 tonnes of rice straw and husks	1.7 million tonnes of cassava stalks
	Ethiopia	1.2 million tonnes of millet straw	815,000 tonnes of wheat straw	610,000 tonnes of maize straw
	Egypt	2.6 million tonnes of wheat straw	1.2 million tonnes of rice straw and husks	553,000 tonnes of maize straw
Asia	India	23 million tonnes of rice straw and husks	21 million tonnes of wheat straw	20 million tonnes of cotton stalks
	Indonesia	28 million tonnes of rice straw and husks	3.5 million tonnes of coconut shells	1.2 million tonnes of maize straw
	Pakistan	224,000 tonnes of cotton stalks	136,000 tonnes of wheat straw	45,000 tonnes of rice straw and husks

A comparison of the three continents covered by our study shows that the composition of agricultural residues varies considerably due to differences in the agricultural structure of the countries in question. While Africa primarily produces millet straw and cassava stalks, large quantities of soybean and maize straw are available in South America. These crops are among the most important biomass sources there, although we exclude a large share of the waste because it originates from the production of animal feed and energy. In Asia, rice straw and husks as well as cotton stalks are the most common types (Fig. 11). As this continent generates by far the largest amount of agricultural residues – 150 million tonnes of dry matter per year – Asia also shapes the composition of the entire Global South (Fig. 11).

Table 5 shows which types of agricultural residues are most common in the countries with the largest populations on each continent. Despite significant variations, soybean production is dominant in Brazil, while maize straw is among the most important agricultural residues not only in Brazil but also in Mexico and Colombia. In Africa's most populous countries, millet, wheat and rice residues account for the largest share of all crop residues. In India and Indonesia, large quantities of husks and straw from rice production are available for climate applications. The hot and dry climate of Pakistan, as well as India, could make use of large quantities of woody cotton stalks, which are particularly suitable for the production of BtL kerosene, but are also well-suited for the production of biochar and electricity. Some countries specialise in the production of a specific crop that, globally speaking, generates a lower volume of residues. This is the case, for example, with coffee husks in Colombia or coconut shells in Indonesia.

Table 6 uses five examples of different crops to illustrate how we calculate the usable biomass from total agricultural production across several filtering

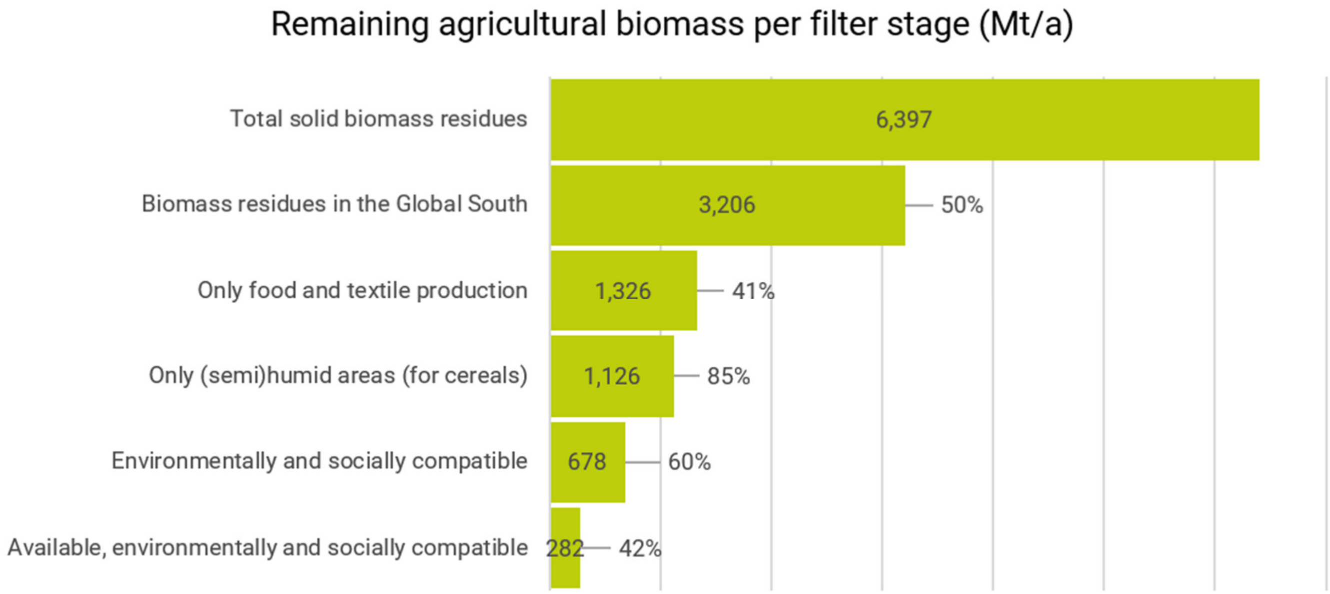

Figure 12: Quantity of biomass from agricultural production left over at each filter stage of our quantity estimation, as well as the percentage change compared to the previous stage

stages. When considering the same biomass across different countries, it is striking that the factors *ESf* and *Af* vary considerably from country to country.

- Cereal straw plays an important role as a natural fertiliser, particularly in dry areas with nutrient-poor soils. We therefore exclude all cereal residues in arid regions and half in semi-arid regions. Since there is generally less agriculture in countries with arid regions, the impact of excluding these residues is only minimal.
- Since the environmental and social compatibility of agricultural residues is in most cases determined using a study that generally underestimates this sustainability compared to our interviews (*ESf* priority level 4), the environmental and social compatibility factor also has a very restrictive effect as it further excludes half of the quantity in question.
- With regard to availability, the general study used also has the most restrictive effect, as it makes no distinction between individual crops (*Af* priority level 4). Furthermore, it only takes into account the share of agricultural residues that is burned and most likely underestimates the amount that can actually be used. Where data from interviews or country- and crop-specific literature sources on alternative uses are available (priority level 1-3), this step is less restrictive.

Main reasons for excluding agricultural residues

In our volume estimate, out of a global total of 6 billion tonnes of solid agricultural residues, only 283 million tonnes (i.e. just under 5%) ultimately meet our – strict – criteria. This is because roughly half of the biomass is eliminated at each of the four key selection stages (Fig. 12).

The individual selection steps primarily involve the following:

- Just by excluding countries in the Global North, a full three billion tonnes of total solid biomass are not taken into account at all. China and the USA, both major agricultural producers, alone account for around one billion tonnes each.
- The exclusion of residues from energy and animal feed production means that only a small part of the very large quantities of maize and soybean residues found worldwide is taken into account, namely the portion that serves directly as food for humans. The result is that an entire one billion tonnes in the Global South is excluded; nevertheless, both crops dominate agricultural residues in Latin America. The complete exclusion of sugar cane and oil palm residues from our estimate accounts for a further 628 million tonnes.

Table 6: Sample calculation of the environmentally and socially compatible and available biomass from various crops.

Crop grown	Country	Total crop production (million tonnes/year)	Type of biomass	*RPR*	Moisture content	Dry biomass (million tonnes/year)	Of which biomass from food and textile production, i.e. not from biofuel or animal feed production (million tonnes/year)	Of which biomass in (semi-)humid regions, used solely for cereals (million tonnes/year)	Of which environmentally and socially compatible (million tonnes/year)	Of which available (million tonnes/year)	Percentage of environmentally and socially compatible and available biomass
Wheat	Nepal	2	Straw	1.2	15%	2	2	2	1	0.3	15%
Maize	South	16	Straw/husks/cobs	2.47	14%	34	4	3	2	0.8	2%
Cassava	Nigeria	61	Stems	0.2	15%	10	10	10	8	2	16%
Cotton	India	15	Stems	4	17%	50	50	50	32	20	41%
Rice	India	196	Straw/husks	0.7/0.2	13%/2%	158	158	128	102	23	15%

6.2. Wood residues

The calculation of available environmentally and socially compatible wood residues is essentially carried out in a way similar to what is shown in Table 6 using agricultural residues as an example. However, in this case, we do not multiply these residues by an availability factor, but instead subtract the quantity that could be recycled into chipboard and fibreboard in the respective region from the environmentally and socially compatible biomass. In the interest of simplicity, we assume that equal percentages of the various types of residues can be recycled into boards, although there may well be differences here. Figure 13 shows the available, environmentally and socially compatible wood residues for various types of wood products by continent and across the entire Global South.

When looking at the total quantities, it is immediately apparent that Latin America, with 50 million tonnes per year, generates almost as many wood residues as the much more populous Asia. In Latin America, timber production for export plays a more significant role than for domestic consumption, which is reflected in the particularly high proportion of roundwood residues. However, these account for the largest proportion of all wood residues on every continent, as a considerable amount of waste is generated when tree trunks are cut up. The production of plywood, chipboard and fibreboard, on the other hand, is most prevalent in Asia.

In Africa, we find by far the lowest volume of wood residues, at 14 million tonnes. This is primarily because the statistical figures for timber production there are relatively low. The main reason, however, is the low percentage of wood residues that can be classified as environmentally and socially compatible according to a World Bank study that classifies the majority of logging on the continent as illegal (World Bank 2019, 43). Even if this study were to overestimate the problem of illegal logging, it is still suitable for our principle of conservative estimation. Given the small total volume of wood residues, the five million tonnes of shrubwood that can be harvested annually for the restoration of grass savannahs in the two countries of Namibia and South Africa (Stafford *et al.* 2017, 4) account for 37% of all wood residues in Africa.

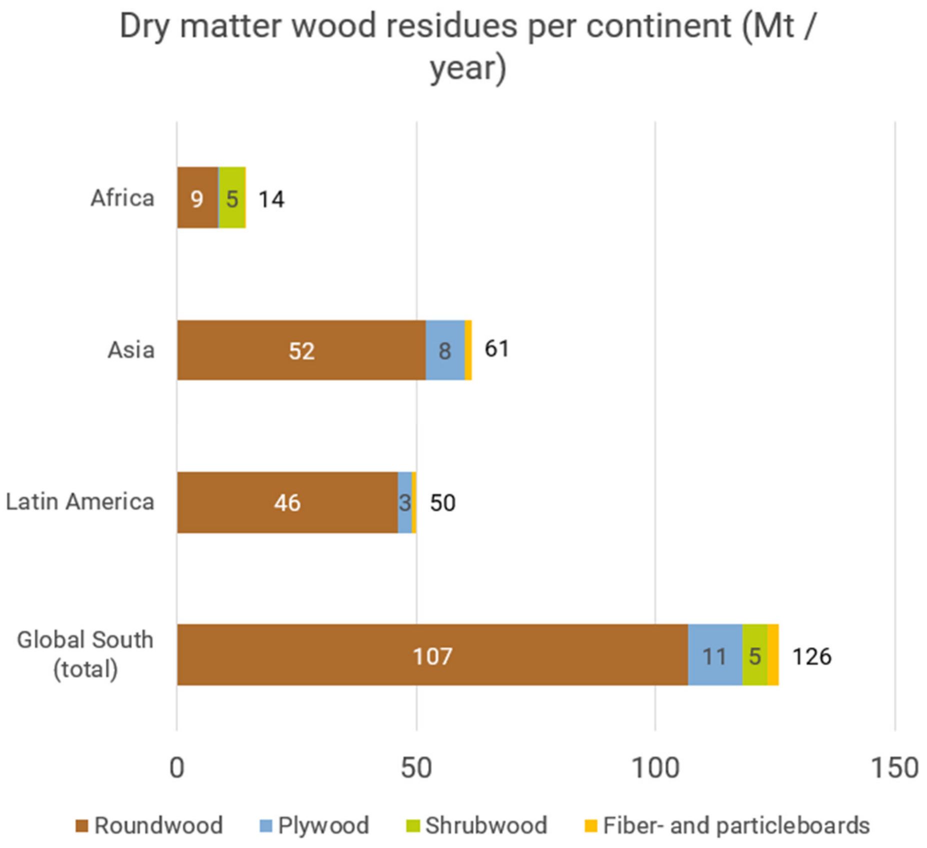

Figure 13: Annual dry matter of available, environmentally and socially compatible wood residues by continent and type of wood product.

Most important reasons for excluding wood residues

Figure 14 shows which steps have the greatest impact when excluding wood residues. It is striking that – unlike agricultural residues – the steps in the selection process vary in how restrictive they are. When selecting countries in the Global South, this means that around two-thirds of the wood residues recorded in the FAO database are excluded compared to the global total. Wood products are primarily manufactured in the Global North, where most forests are located.

Figure 14: Quantity of biomass from timber production left over at each filter stage of our quantity assessment, as well as the change in percentage compared to the previous stage

If we apply our environmental and social compatibility criteria to all wood residues in the Global South, we must exclude one third, which originates from illegally cut trees. This is less than for the respective filter stage for agricultural residues, which is likely due to the fact that environmental and social compatibility in agricultural production comprises several dimensions, whereas for wood products derived from illegal logging, it comprises only one. Of the environmentally and socially compatible wood residues, around 90% is available for climate applications, after subtracting the quantity that could be recycled into chipboard. In the Global South, neither of these is (yet) produced in sufficient quantities to recycle a significant share of wood residues.

Box 13: Use of shrubwood cuttings in Africa

There are no global studies on the total area of grass savannahs covered by shrubwood, only case studies for individual countries or regions. We have taken into account only South Africa and Namibia, which have the world's largest total production of shrubwood and have been studied accordingly. Our analysis incorporates a conservative estimate suggesting that just under three million tonnes of woody biomass could be harvested annually in each of the two countries (Stafford *et al.* 2017, p. 4), which would only partially clear the affected areas of shrubwood – in line with our sustainability principles. However, there are different estimates regarding the potential of shrubwood cuttings: The PtX Hub estimates annual potential of 17 million tonnes of shrubwood cuttings for Namibia alone (Kyriakarakos *et al.* 2023, 23).

Overall, following our principles, 19% of total global wood residues can be used, which is significantly higher than the 5 per cent of agricultural residues. This is primarily because the environmental and social compatibility factor *ESf* has a less selective effect here. The differences in the effectiveness of the availability criterion are – in addition to the more versatile uses of agricultural residues – likely attributable to different processing methods. In the case of agricultural residues, we take the waste that is burned for the majority of the rows, which means we are most likely underestimating the amount of residues that can actually be used. In the case of wood residues, however, we only subtract the amounts that could actually be recycled and reused, which means we are unlikely to underestimate the actual usable residual amount.

6.3. Sewage sludge

In the countries of the Global South we studied, we calculate a total of just under 10 million tonnes of dry sewage sludge per year (as of 2015), which could potentially be combusted, gasified or even converted to biochar for electricity generation. The largest quantities are found in Brazil, Egypt and Indonesia, with over one million tonnes per year in each case. Brazil and Egypt are countries with large populations and relatively well-developed infrastructure, where the amount of sewage sludge stands at 9 and 14 kilograms per inhabitant respectively. In Indonesia, by contrast, we calculated only 3 kilograms per inhabitant, which can be attributed to a lower percentage of wastewater being treated at all. At the

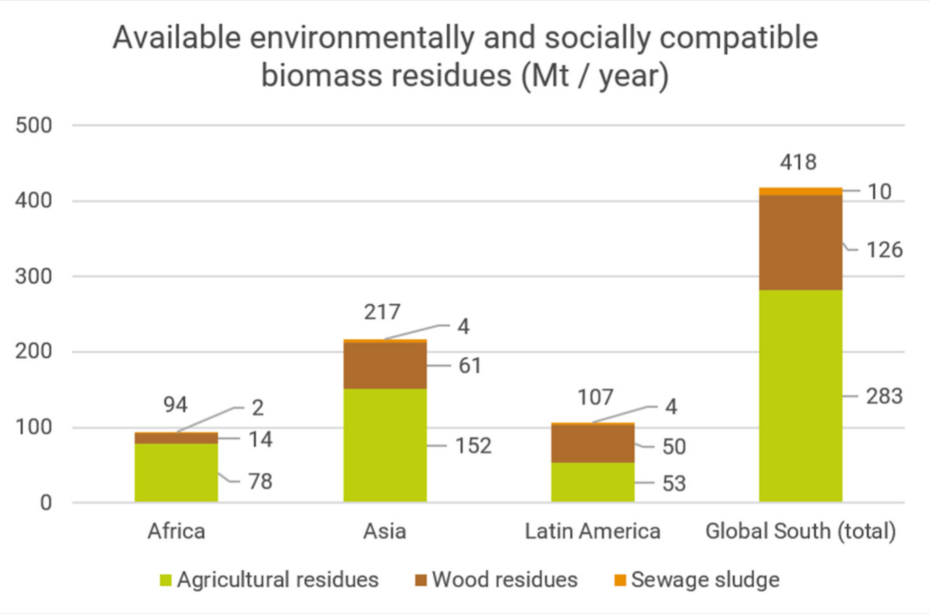

Figure 15: Quantities of total available environmentally and socially compatible biomass by continent and across the entire Global South.

bottom of the rankings[1] in terms of absolute sewage sludge volume are countries such as Nigeria, the Philippines and Bangladesh, where the percentage of wastewater treated is low, according to Jones *et al.* (2021). This highlights the vast differences in wastewater treatment across the Global South. By way of comparison: in Germany, wastewater treatment plants filter out around 20 kilograms of sludge per inhabitant from wastewater every year (Eurostat 2023). The exclusion of countries in the Global North has a significantly more pronounced effect on sewage sludge than on agricultural and wood residues. This step in narrowing the focus eliminates a full 37 out of 47 million tonnes. This is because sewage systems are more widespread in these countries and a significantly higher share of their wastewater is treated in treatment plants.

It is important to note, however, that both the data on the volume of treated wastewater and the calculation of the volume of sewage sludge are based solely on estimates. We determine the volume of sewage sludge by multiplying the volumes of treated wastewater estimated by Jones *et al.* (2021) with a factor based on the median value for EU countries, as no corresponding data exists for countries in the Global South. However, it is possible that the amount of sewage sludge per volume of wastewater varies across different countries due to differences in treatment technology. On the other hand, it can be assumed that the estimates based on 2015 are no longer up to date and that the volume of sewage sludge is now higher. Since then, the population has grown – and the wastewater infrastructure in countries of the Global South has likely also been expanded.

6.4. Summary: Usable biomass for climate applications

Figure 15 shows the total quantities of all three categories of biomass by continent. The populous continent of Asia offers a potential of over 200 million tonnes of usable solid biomass. Africa and Latin America each account for approximately 100 million tonnes of biomass per year. In terms of composition, it is evident that wood residues play only a minor role in Africa, whereas in Latin America they account for almost half of all usable biomass. As regards the type of biomass, it is notable that agricultural residues are the most significant, followed by wood residues. Dried sewage sludge accounts for the smallest amount of solid biomass, at two per cent.

Figure 16 draws on the diagram of the procedure from Chapter 2.3 on methodology and shows how we gradually reduce the quantity of usable biomass in several stages. The diagram does not show the focus on solid biomass, as there are only rough estimates of the global total volume of wet residues (aside from sewage sludge). According to estimates, 1.05 billion tonnes of food waste are generated each year in households, the retail sector and the hospitality industry (UNEP 2024, 46), and three billion tonnes of animal manure (FAIRR 2022). This means that just under 12 billion tonnes of biomass are generated

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[1] Jones *et al.* (2021) were unable to estimate data on the volume of treated wastewater for all the countries covered in the study.

worldwide each year, of which 7 billion tonnes are solid residues (including dried sewage sludge). We reduce these 7 billion tonnes in three steps, leaving just over 400 million tonnes per year. The total quantity decreases by half with each step, or in one case (the environmental and social compatibility factor) even to a quarter. We cannot provide a specific figure for the economic potential, but we offer some considerations on this in the following discussion.

These 418 million tonnes of solid biomass have an energy content of 7.73 EJ, which is significantly lower than in previous estimates of global biomass potential (Chapter 2.2). Table 7 shows how they could be used for various climate applications.

The table shows that the most fossil CO_2 can be prevented with our solid biomass if it is used in a power plant. However, this is only the case if a region's electricity has previously been generated exclusively or largely from fossil sources such as coal. In terms of efficiency, however, combustion in a biomass power plant is the least efficient, as a great deal of energy is lost in the form of heat. In countries where buildings need to be heated, however, this energy could be used for district heating, which would result in significantly higher efficiency. If a large share of a region's electricity mix already comes from renewable sources, it would make more sense to convert the biomass to biochar or to synthetic hydrocarbons such as kerosene using BtL processes.

Table 7: Quantitative potential for various climate applications for 418 million tonnes of solid biomass with an energy content of 7.73 EJ

Climate application	Overall energy efficiency[1]	Total volume of end products	Energy content of end products (EJ)	Energy content of end products (Twh)	Contribution to climate change mitigation
Combustion or gasification to electricity	30%[2]	645 TWh electricity	2.32	645	saves 580 million tonnes of CO_2[3]
Gasification to synthetic hydrocarbons[4]	34%	60 million tonnes of hydrocarbons (of which 40 million tonnes is kerosene)	2.6	720	saves 180 million tonnes of CO_2[5]
Pyrolysis to biochar[6]	60% (coal + electricity)	125 million tonnes of coal + 150 TWh electricity	4.71 (coal + electricity)	1,315 (coal + electricity)	sequesters 350 million tonnes of CO_2 equivalent in the soil in the long term + saves 135 million tonnes of CO_2[7]

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[1] Energy efficiency relates the energy content of the end product (electricity, hydrocarbons or biochar) to the energy content in the dry biomass.

[2] Typical efficiency for newer biomass power plants with direct combustion (Jenkins *et al.* 2019)

[3] Assuming that the electricity would otherwise be generated using lignite, that the lignite-fired power plant has an efficiency of 40% (BUND 2022), that one tonne of lignite contains 12 GJ of energy, and that the combustion of 1 t of lignite releases 1.2 t of fossil CO_2 (Greenhouse Gas Institute 2024).

[4] Based on experiments and calculations of Solarbelt gGmbH.

[5] When combusted, 1 tonne of kerosene releases 3.16 tonnes of CO_2, and 1 tonne of other hydrocarbons releases 2.7 tonnes of CO_2 when combusted or decomposed.

[6] Based on experiments and calculations of atmosfair gGmbH.

[7] Assuming that the electricity would otherwise be generated using lignite, that the lignite-fired power plant has an efficiency of 40% (BUND 2022), that one tonne of lignite contains 12 GJ of energy, and that the combustion of 1 t of lignite releases 1.2 t of fossil CO_2 (Greenhouse Gas Institute 2024).

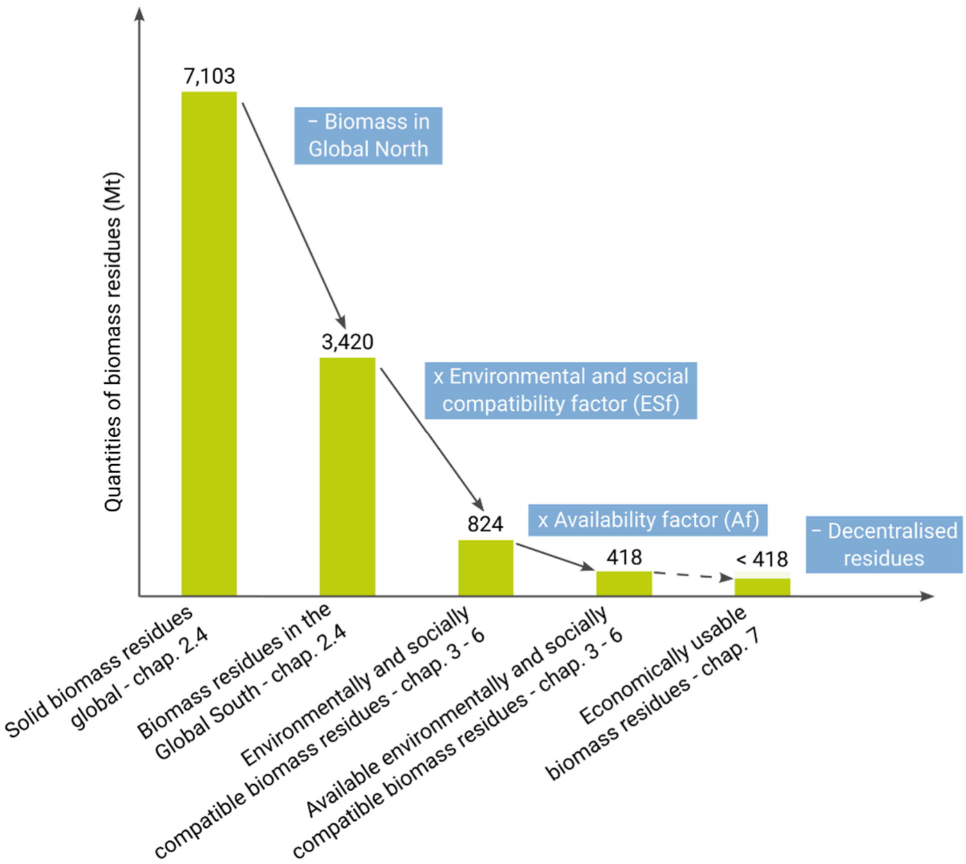

Figure 16: A step-by-step restriction to particularly useful biomass, using figures from our survey.

Biochar has the advantage that it can permanently sequester CO_2 from the air in the soil. Such negative emissions contribute even more to climate change mitigation than simply preventing emissions, and are a necessary component in achieving the net-zero target by 2050 or earlier. In addition, the wood gases released during pyrolysis can be burned to generate electricity and replace fossil fuels.

The BtL process has an overall energy efficiency of 34%, provided we take into account not only the kerosene but also the energy in other fuels and plastics that can be produced from the molecules of the Fischer-Tropsch synthesis. Around 65% of the Fischer-Tropsch output can be processed into kerosene, which would prevent 125 million tonnes of fossil CO_2 emissions from aviation. These are hard-to-abate emissions that can currently only be made CO_2-neutral using BtL kerosene.

Given that there are CO_2-free options for electricity generation, BtL production generally appears to be a sensible climate application. The CO_2 savings from hydrocarbons are not limited to aviation or fuels.

These precise figures should not give the false impression that an exact calculation of the potential for biomass is available. This is merely an estimate, which is why a range of possible values would be more appropriate. However, as we can only derive individual values and not ranges of values from the literature for the factors relating to environmental and social compatibility and availability, we also express our results as individual values.

Estimation of the energy potential of wet residues

To gain a broader picture of the energy potential of all biomass from residues, we conclude by calculating, based on estimates for food waste and animal manure (FAIRR 2022, UNEP 2024), what climate potential these wet residues could offer.

In the interest of simplicity, we assume that half of all wet residues are generated in the Global South, i.e. 2 billion tonnes. Both animal manure and food waste can be used as biofertilisers, replacing greenhouse gas-intensive mineral fertilisers. However, this use does not compete with biogas production: the residues from the biogas plant still contain sufficient nutrients to then be spread on fields. The availability factor Af should therefore be set at 100%

If we consider the use of food waste to be fully environmentally and socially compatible and the use of animal manure to be half as environmentally and socially compatible[1], we arrive at an available, environmentally and socially compatible quantity of 1.25 billion tonnes per year. Although the total volume of wet residues is lower than that of solid residues, a significantly larger share meets our criteria because we consider *Vf* and *Nf* to be less restrictive for wet residues. These residues could yield approximately 90 billion m^3 of biogas in biogas plants, which in turn could generate 200 TWh of electricity.[2] This use could therefore save roughly 180 million tonnes of CO_2 annually.

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[1] The exclusion of biomass from energy production, which we apply to agricultural residues, does not apply for wood residues.

[2] For food waste, we assume a biogas yield of 100 m^3/t, and for animal manure, 50 m^3/t, with methane accounting for 60% of the biogas. The calorific value of methane is 9.97 kWh/m^3, and a combined heat and power plant achieves an efficiency of around 40% with biogas. Based on calculations by atmosfair.

7. Discussion of economic feasibility and conclusions

This study shows that over 400 million tonnes of environmentally and socially compatible biomass with an energy content of 7.73 EJ are available every year in the Global South. Other studies have calculated larger quantities of biomass (Chapter 2.2), due to the fact that we apply stricter criteria for environmental and social compatibility and availability, and limit our scope to the Global South. However, we can be certain that the amount of biomass from residues calculated here could actually be used for climate applications.

These solid residues can be used to produce 125 million tonnes of biochar, 645 terawatt-hours of electricity or 60 million tonnes of hydrocarbons, including 40 million tonnes of kerosene with an energy content of 480 terawatt-hours (Table 7). Our study shows that the amount of kerosene that could be produced using BtL could meet 20% of global demand for aviation fuels (Fig. 17), which would improve the carbon footprint of aviation, at least in part. Global kerosene consumption is expected to reach 390 million tonnes by 2040 (Hungerland *et al.* 2024, 25f.), 10% of which could still be met by biomass from 2022. However, this would only be possible if the BtL kerosene, which can be produced in limited quantities, were used solely for aviation and not for internal combustion engines in road transport, where electric drives are much more efficient.

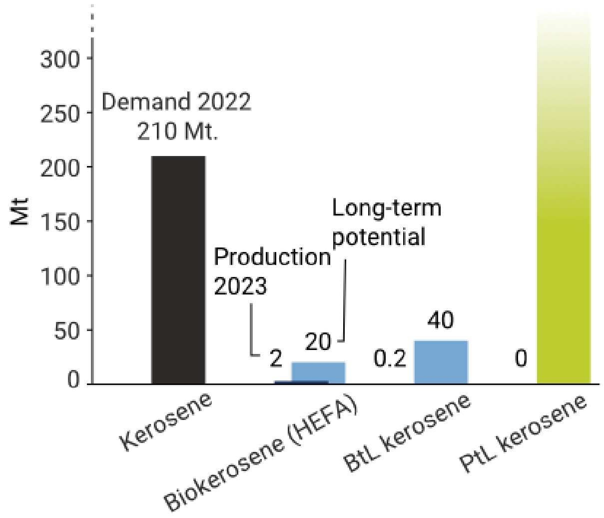

Figure 17: Currently possible production volumes of SAF fuels, as well as their long-term production potential and current global demand for kerosene. In theory, large quantities of PtL kerosene could be produced, which would exceed the aviation sector's demand many times over. This would be contingent on sufficient production of green electricity (CENA 2023, 11, Statista 2024).

Depending on where it is used, however, it may make more sense to convert the residues to biochar or use them for electricity generation. The latter merits a more nuanced view: the total amount of electricity that can be generated from our residues is rather low, amounting to 2.5 times Germany's total renewable electricity production (254 TWh) or 8% of the renewable energy generated worldwide (8,524 TWh) in 2022 (BMWK 2023, 18/93). Energy generated by solar power plants is more efficient than biomass electricity generation, particularly in the sunny countries of the Global South. However, the use of waste materials in biomass power plants can pay off where there are industries that require a baseload energy supply for their production. In these niche markets, biomass from residues – despite its limited quantity – has the potential to create new development opportunities for the economy.

Economic potential of biomass for climate applications

In practice, climate applications are only feasible if the prices of end products such as electricity, BtL kerosene or fertiliser based on biochar are competitive. This is the case when the costs of biomass do not exceed a certain limit. The costs of biomass comprise the following components:

1. Purchase price of biomass

Box 14: Prices of cashew shells and mustard straw

A pilot project by Solarbelt FairFuel gGmbH on the use of cashew shells for energy production found that the price of biomass can be highly volatile: it fluctuated between 0 and 60 euros per tonne in the space of a year, primarily due to varying levels of competition among buyers.

In Rajasthan, India, mustard straw is used for electricity generation in a project supported by atmosfair gGmbH. A tonne of mustard straw costs between 25 and 28 euros there; these prices have therefore stabilised over many years.

2. Logistics costs, i.e. transport and storage of biomass
3. Costs for further processing, which is required for some types of biomass (e.g. crushing or turning into pellets prior to gasification)

This is not a quantitative calculation of the economic potential of actual biomass, we are merely considering the transport costs. However, the economic potential is in any case smaller than the available quantity of residues that we calculated in Chapter 6.

To assess the economic potential of biomass based on transport costs, we group all types of residues into one of three categories, depending on whether they tend to be concentrated in a few locations or distributed over large areas. We make the simplified assumption that certain crop residues are found equally in centralised or decentralised locations across all countries.

Distribution of biomass

Generally speaking, the economic use of biomass is most efficient when it is generated at a specific point, allowing larger quantities to be collected at once. This is particularly the case at processing plants, where, for example, cashew shells or rice husks are produced as residues. However, wood residues from sawmills and sewage sludge also fall under the category of centrally located biomass (Fig. 18). Our classification simplifies reality, as differences in geographical concentration can also exist among processing plants. Rice mills, for example, are predominantly small businesses in some countries, which may be scattered across a rice-growing region, making it more expensive to develop them. Furthermore, cultivation and processing may take place in different countries. Cashew nuts, for instance, are in some cases not even shelled in Ivory Coast, their country of origin, but in India, where they are imported. However, when assessing global potential, it is not particularly important which country the biomass ultimately originates from.

Semi-centrally available biomass consists of waste generated during the first processing stage on farms, such as cereal straw or cocoa and soybean pods. Even though this waste is also generated at individual points, the logistics involved can still be complex, particularly in smallholder agriculture, where a large number of small farms need to be visited. The most work is needed to collect crop residues scattered across entire fields. In addition to cotton and cassava stalks, this also includes shrubwood. However, decentralised biomass accounts for only a quarter of the total quantity we have estimated, while semi-centrally and centrally located residues, which are more efficient to procure, each account for 40%.

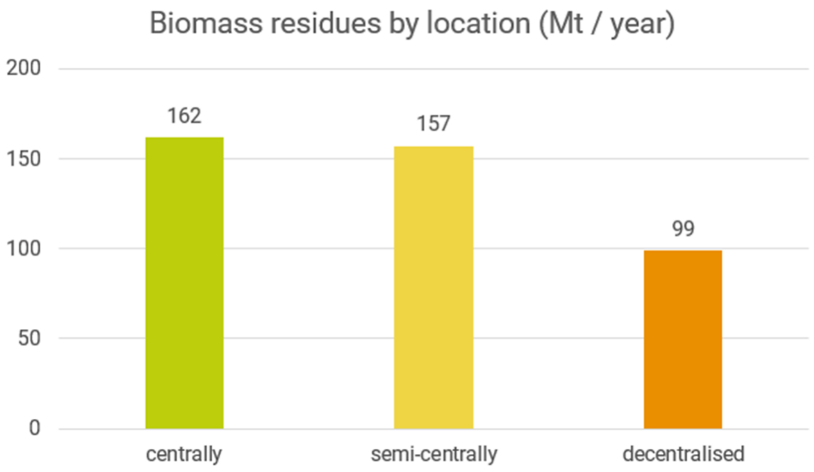

Figure 18: Location of available environmentally and socially compatible biomass.

The local sourcing of agricultural residues presents a challenge to our commitment to social compatibility: On the one hand, we want to support smallholders above all, but collecting agricultural residues from such a large number of small farms is not very efficient. Residues from large-scale farms can be sourced with less effort, but these farms generally have less need for financial support. Cooperatives would also be an attractive option for small farms when it comes to selling harvest residues, enabling them to organise their trade more efficiently.

In addition to the actual transport costs, crops that are only harvested at certain times of the year also incur storage costs until the biomass is required for combustion in power stations or for gasification. Furthermore, certain types of biomass may need to be pre-treated and converted, for example, into a form suitable for gasification, which involves additional costs. For instance, rice husks first need to be pressed into pellets or coconut shells crushed before they can be fed into a BtL plant. However, this pre-processing also reduces the volume and weight of biomass, making it cheaper to transport (van Dyk/Saddler 2024, 38f.). Due to all these cost factors, it is possible that some environmentally and socially compatible biomass available in the Global South may not be economically profitable, particularly if the biomass is processed centrally.

BtL plants, biomass power stations and industrial pyrolysis plants are centralised facilities that source their biomass from a wider surrounding area. For them, the use of decentralised biomass may not be cost-effective, as transport costs are higher when agricultural residues have to be collected from many individual villages. The situation is different, however, when it comes to decentralised use, which atmosfair encourages, for example, in its biochar project in Ghana. We have equipped 300 villages there with small-scale pyrolysis plants, which people use to process their crop residues into biochar directly on site. This can be used as a soil improver on the fields in their village. This allows biomass to be used for climate change mitigation without incurring high costs for collecting large quantities of decentralised residues.

Production costs of BtL kerosene

BtL kerosene is the most cost-intensive of the three climate applications considered here, which is why we are taking a closer look at its competitiveness. A study by the World Economic Forum (2020) estimated the cost of one tonne of BtL kerosene at approximately 2,000 US dollars, while the price of kerosene at the time of the study (in 2019) fluctuated between 600 and 700 US dollars. However, compared with other Sustainable Aviation Fuels (SAF), BtL is certainly competitive (Fig. 19).

Box 15: Future trends in biomass waste volumes

It is reasonable to assume that the total volume of biomass waste will increase rather than decrease in future, as the demand for food – and therefore food production – will rise in line with the continuing growth of the world's population. The volume of sewage sludge will also increase in future, both as a result of population growth and the expansion of wastewater treatment systems.

With regard to the environmental and social compatibility of biomass, it can be said that the proportion of organic farming has risen in recent years (Meier *et al.* 2022, 51). This increase could be sustained even with an overall higher demand for food. However, given the limited amount of agricultural land, this will only be possible if humanity switches to a more efficient and meat-free diet.

The expected future costs of PtL kerosene, and thus its competitiveness, depends on the locally available potential for renewable energy, which is why the range spans from 1,500 US dollars to almost 6,000 US dollars per tonne. However, further expansion of renewable energy and economies of scale are also expected to drive costs down in this area. Unlike BtL and, in particular, HEFA fuels, PtL kerosene has the advantage that its theoretical potential (i.e. the renewable energy available on Earth) far exceeds the energy requirements of aviation (Fig. 17). In the European Economic Area, PtL plants are currently planned that are expected to produce a total of 1.7 million tonnes of e-kerosene per year by 2030 (Transport and Environment 2024, 8ff.). However, it is uncertain whether these capacities will actually be established by then.

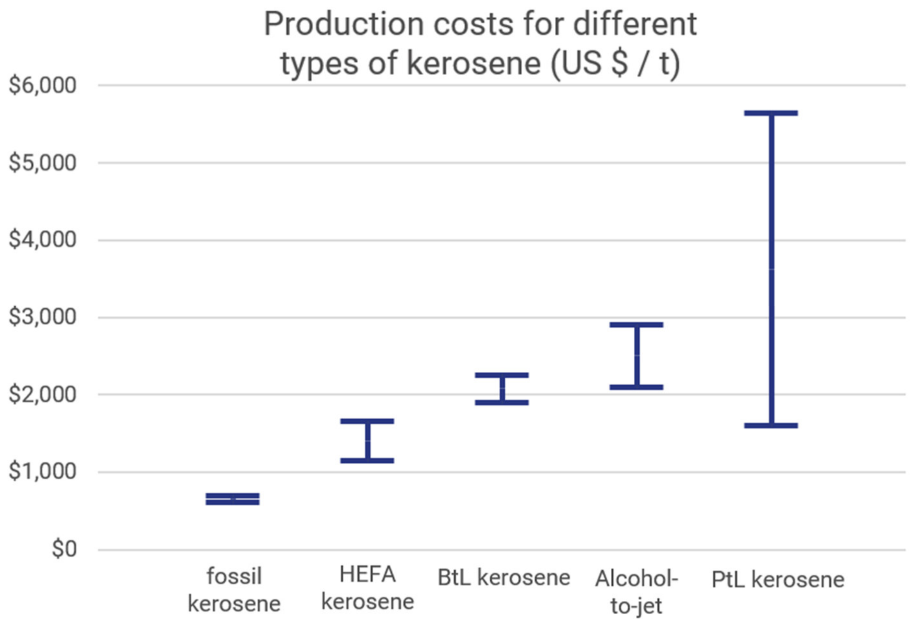

Figure 19: Comparison of production costs for different types of kerosene. HEFA stands for "hydrotreated esters and fatty acids" derived from waste fats or oil crops (Wolff/Riefer 2020, 34, EIA 2024)

HEFA kerosene is generally cheaper to produce, but is considered problematic if the fatty acids are not derived from waste but from energy crops such as oil palms. If HEFA is produced exclusively from waste fats, the quantities available worldwide are more limited than the potential for BtL kerosene from biomass calculated here (Fig. 17). Alcohol-to-jet kerosene is more expensive to produce than BtL fuel and is mainly produced from energy crops grown specifically for this purpose. Consequently, it cannot seriously compete with kerosene produced via gasification and Fischer-Tropsch synthesis, either in terms of environmental and social compatibility or production costs.

Given the expected production costs of PtL kerosene, the total price per litre of BtL aviation fuel should not exceed 3 euros (EIA 2024). As things stand, this limit can be met if the cost of the biomass used in the BtL plant does not exceed 100 euros per tonne of dry matter. However, the costs of kerosene production overall do not depend solely on the biomass itself, the purchase price of which, according to initial estimates, accounts for approximately 10 to 20% of the final product. The technology and efficiency of the BtL process itself also play an important role here.

Restrictive limits due to conservative estimates

Previous studies estimating the total biomass potential from residues put it at between 20 and 50 EJ per year (Chapter 2, Table 1). Furthermore, the energy content of our agricultural residues, at 7.7 EJ, appears rather low. This is partly because other studies impose restrictions regarding environmental and social compatibility or availability. We apply both types of criteria, which reduces the total amount more significantly. On the other hand, previous studies look at global biomass production, whereas we focus on the Global South. In the Global North, a further 320 million tonnes of in-principle suitable agricultural residues might be generated annually (in addition to the 283 million tonnes in the Global South), with 225 million tonnes of this alone in the USA and China.[1]

In line with the principle of conservative estimation, it is better to calculate a smaller quantity that can be used in a way that is guaranteed to be environmentally and socially compatible. It can be assumed that, in reality, more residues would be usable than we have calculated in our study, for the following reasons:

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[1] Assuming that 10% of biomass would remain after sustainability and availability assessments.

- We have generally classified certain types of biomass, such as oil palm residues and sugar cane bagasse, as unacceptable and have excluded them entirely from our analysis. However, it could also be argued that the use of such biomass is acceptable, provided that they are grown in accordance with environmental criteria. Even if these are not foodstuffs necessary for a balanced diet.
- Other residues such as maize straw and soybean pods or straw were included only to a small extent, which corresponds to direct food production for humans. It remains to be discussed whether the purchase of biomass from feed or energy crop production is a pull factor for the expansion of these crops, or whether this biomass would be acceptable under certain conditions, such as organic farming.
- For many countries, there were no interviews or literature sources available on alternative uses of biomass. We therefore relied on data related to burning of crop residues, a share that can be considered reliably available. However, it must be assumed that significantly more biomass is available which, while not being burned, is also not put to alternative use and, for example, rots at the edge of the field.

The SAM study on the quantification of sustainable agriculture is an analysis that applies to all crops grown in a country. However, growing conditions can vary significantly between different crops within the same country. Depending on the country, even the same crop can be grown and processed in ways that vary in terms of their environmental impact, as demonstrated by the examples of cotton and coffee, among others (Chapter 4.1). Various sustainability labels can be used to assess the respective crops in greater detail (Meier *et al.* 2022). However, as the criteria for the individual labels differ from one another, they are unsuitable as a basis for a general study like this one.

Quantitative potential of wet residues

The amount of environmentally and socially compatible biomass available for climate applications would be even greater if wet residues such as animal manure and food waste were also taken into account. The 1.25 billion tonnes from our estimates (Chapter 6.4) can primarily be used to mitigate climate change in the form of biogas, which replaces fossil fuels as cooking gas or in a biogas power plant. Biogas can even be used for SAF production, as methane can be converted to methanol, which is the feedstock for the innovative methanol-to-jet-fuel process.

Our analysis provides a conservative estimate of the total globally available quantity of environmentally and socially compatible biomass. However, if a particular biomass appears to be of interest for climate applications, our highly generalised analysis should not be consulted. Instead, it would make more sense to consider the individual case. It is possible that a particular crop in a specific region may well be classified as environmentally and socially compatible, even though it was generally deemed unacceptable in our study. The sustainability principles set out in Chapter 3.2, together with their individual criteria, also provide a suitable framework for these case-by-case assessments of the environmental and social compatibility of biomass. However, there will never be an ideal case of biomass that is 100% environmentally and socially harmless, which is why certain compromises are necessary. That said, sustainably used biomass from residues has enormous potential to combat climate change while simultaneously promoting energy development in the Global South.

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Data set for this study

You can request the complete data used to calculate the biomass potential by emailing peiker@atmosfair.de orinfo@atmosfair.de for a small fee.