Greenhouse gas emissions from Terra Preta substrates in India

Country Factsheet India

Implemented by

Executive summary

For all investigated concepts, the production and application of the Terra Preta Substrate (TPS) lead to negative emission results under the selected assumptions, resulting from an assumed carbon sequestration that exceeds the greenhouse gas emissions from the production of the TPS. Whereby, the concepts with advanced pyrolysis technology are the most advantageous due to the reduced CH_4 emissions from pyrolysis.

Emissions of methane and nitrous oxide from composting and pyrolysis process are by far the most significant emission sources in the overall result. The result shows a high influence of carbon sequestration in the overall balance. The carbon introduced and permanently sequestered, mainly via the biochar, leads to high CO_2 credits.

TPS production, including pyrolysis and composting processes, and the application to agricultural soils interact with the environment and climate system in multiple complex ways, this results in many uncertainties.

In order to reduce these ranges in the future and to further increase the robustness of the accounting results, measurements of actual emission values or sequestered carbon should be taken regularly during the further implementation and operation of the investigated technologies in India.

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List of Abbreviations

GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
BMZ	Federal Ministry for Economic Cooperation and Development
GHG	Greenhouse gases
TPS	Terra Preta Substrate
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

① Introduction

In 2020 80 % of the total energy demand in India has been supplied by three main different energy sources. These are: fuels coal (15,870,570 TJ), oil (8,682,120 TJ) and solid biomass and wastes (8,200,440 TJ) (International Energy Agency 2020). The most important contribution to India's energy system has been made by coal, which enabled the expansion of electricity generation and industry. Oil resources and imports are mainly used for road transport and are partly correlating with a rising number of transport vehicle ownerships in India. Biomass, especially fuelwood, is mostly used as cooking fuel. The transformation to modern, clean cooking gases is under progress and might need more time until expanded coverage (International Energy Agency). Furthermore, energy sources with smaller shares are natural gas (2,201,934 TJ), hydropower (579,272 TJ), wind- and solar power (516,549 TJ) and nuclear power (409,407 TJ) (International Energy Agency 2020).

About 70 % of the population in India depend on biomass to meet energy needs. Due to the potential and role of biomass energy in the country, the ministry of new and renewable energy (by the government of India) enrolled a number of programs to promote efficient technologies and to reach the optimum use for the country's biomass resources for grid power generation. Relevant biomass sources used in India are bagasse, rice husk, straw, cotton stalk, coconut shells, soya husk, press cakes, coffee waste, jute waste, groundnut, saw dust etc. The current availability of biomass in India is estimated at approx. 750 million metric tons per year. By including agricultural residues this amount could be added by 230 million metric tons per year which correspond to an energy potential of 28 GW (Ministry of new and renewable energy 2023).

India suffers from soil degradation that is either natural-caused (i.e. by earthquakes, tsunamis, droughts, avalanches, landslides, volcanic eruptions, floods, tornadoes or wildfires) or human-induced resulting from land clearing or deforestation, improper management of industrial effluents and wastes, poor forest management, over-grazing, urban sprawl or inappropriate agricultural practices (i.e. excessive or imbalanced inorganic fertilizer use, heavy machinery use, poor irrigation or water management techniques, inadequate crop residue and/or organic carbon inputs etc.) (Bhattacharyya et al. 2015). The use of compost and biochar may increase the water holding capacity of soils and represents a chance for improved soil fertility which counteracts some kinds of soil degradation. Furthermore, closing nutrient cycles between rural and urban areas (Urban Rural Nutrient Carbon Cycle by giz) in the sense of circular economy by provision of food, nutrient and agricultural goods from the rural regions and carbon and nutrient return from urban organic waste to soils promise ecological gains by improved soil protection, enhanced soil nutrients, carbon sequestration and prevented pollution of air and water. Financial benefits might be reached for farmers, agricultural industries, dealers, transporters and compost enterprises as well as community compost units (giz).

Despite the energy potential, agriculture is the major source of greenhouse gas (GHG) emissions. Main sources of GHG emissions in Indian agriculture are livestock and rice production with a country average of 5.65 kg CO2eq/kg for rice, 45.54 kg CO_2eq/kg for mutton meat and 2.4 kg CO_2eq/kg for milk (Vetter et al. 2017).

The use of renewable energy sources can contribute to further reducing environmental effects and emissions in the agricultural sector India. Furthermore, the utilisation of biogenic residues and wastes for the production of soil improvement materials can significantly contribute to mitigate the loss of organic carbon and soil fertility in India.

Table 1 Country facts

Surface	3.287.263 km^2
Population	1.4 Billion
Arable land	10,7 %

The use of regional biogenic resources to provide substrates for soil improvement in a circular approach offers a great opportunity to reduce the loss of fertile soils in India and to conserve soil carbon and soil fertility. Suitable materials for soil improvement can be generated using diverse feedstock and conversion processes. For India, a number of value chains, based on mixed biogenic waste streams for the production of biochar has been analysed. For these value chains, greenhouse gas emissions (GHG emissions) have been calculated. The aim of the GHG balance was to determine the main influencing factors and drivers and to prepare recommendations for the implementation of appropriate technologies and concepts in India.

Current situation and brief characteristics of the main pathways analysed

The agricultural sector of India provides manifold opportunities and resources that can be used as a starting point for the production of soil improvement materials. This report focusses on the production of Terra Preta substrate (TPS), produced with different approaches and technology options in India. The concepts have been selected and defined together with various local experts and GIZ staff in a joint consolidation phase. Starting point for this process has been an analysis of existing literature. Some data gaps, e.g. average transport distances and material throughput, have been closed due to the involvement of a regional subcontractor in India who conducted site visits and operator surveys.

Main focus of the analysed value chains is on the production of biochar from mixed biogenic garden waste and communal green cuttings. There is currently no terra preta or biochar production on any of the three evaluated sites, but it is assumed that pyrolysis plants and subsequent terra preta production are located on the composting sites. The selected concepts are further described below.

Concept A: Biochar and Terra Preta substrate production with a Kon Tiki approach

The Kon Tiki kiln is an easy to set-up, low-tech pyrolysis option that allows a production start in the short term with relatively low investment costs. The concept for the production pathway is shown in Figure 1.

Basis for the production of biochar in this concept is the use of mixed green waste. After the mixed green waste arrives at the processing site, it is segregated into a woody fraction and leaves.

While leaves are shredded and dried to make briquettes, the woody fraction is sun-dried, cut manually (or automatically) and compressed into bundles mechanically by a diesel tractor. After sun-drying, the bundled biomass is fed manually into Kon Tiki kilns. Once the pyrolysis process is finished, the kilns are quenched with water to stop further carbonization.

The produced biochar is ground by an electric grinding device and mixed mechanically with wet semi-composted biogenic waste to produce Terra Preta Substrate with a biochar content of 20 %wt.

Finally, the produced ground biochar can be distributed further for application in agricultural production systems.

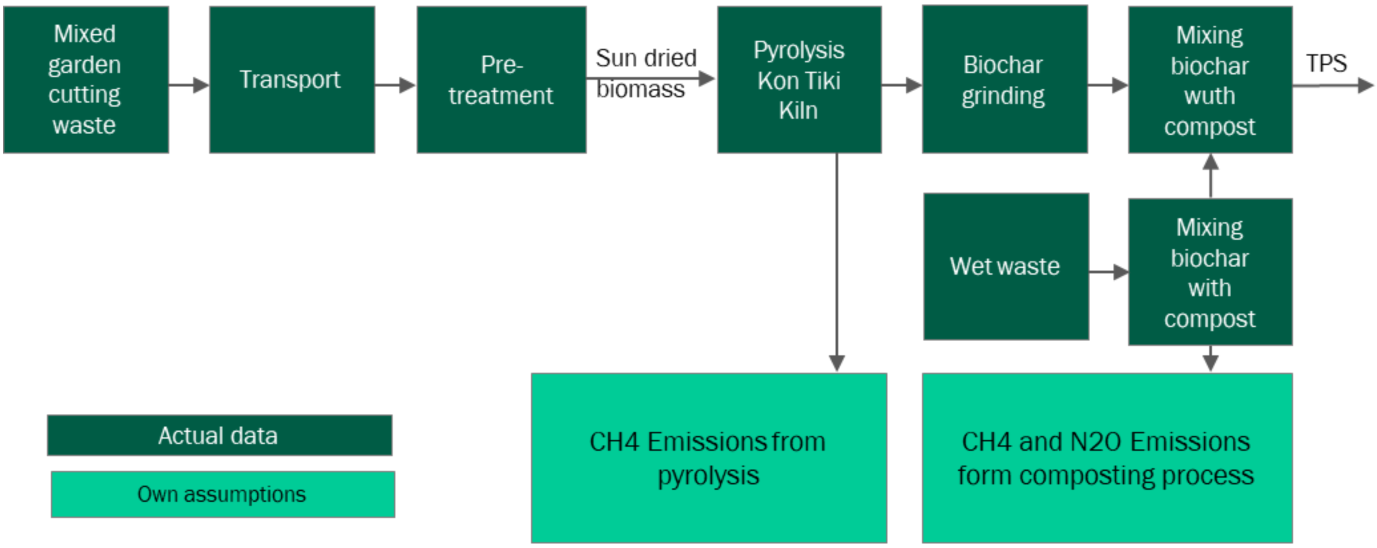

Figure 1 Concepts and involved processes for the production of biochar with the Kon Tiki approach

Concept B: Biochar and Terra Preta substrate production with an advanced approach (Virdarbha 5300 l)

The second analysed concept is characterised by a slightly more advanced technological approach, using a manually fed batch-type pyrolysis reactor of a kiln reactor. This allows exploitation of surplus heat to dry the biomass.

The concept and the involved process steps are shown in Figure 2. As a first step, the mixed green waste is segregated into a woody fraction and leaves. The woody fraction is sun-dried and shredded mechanically by electric shredder. A bundling process is not required in this scenario. The shredded biomass is dried in drying drum and fed into an electric briquetting press. After briquetting and storing in a container, the stored briquetted are fed manually into batch-type pyrolysis.

Surplus heat is generated during the pyrolysis process which is partly used for the drying process via heat exchangers.

The produced biochar is ground by an electric grinding device and mixed mechanically with wet semi-composted biogenic waste to produce Terra Preta substrate. Finally, the produced ground biochar can be distributed further for application in agricultural production systems.

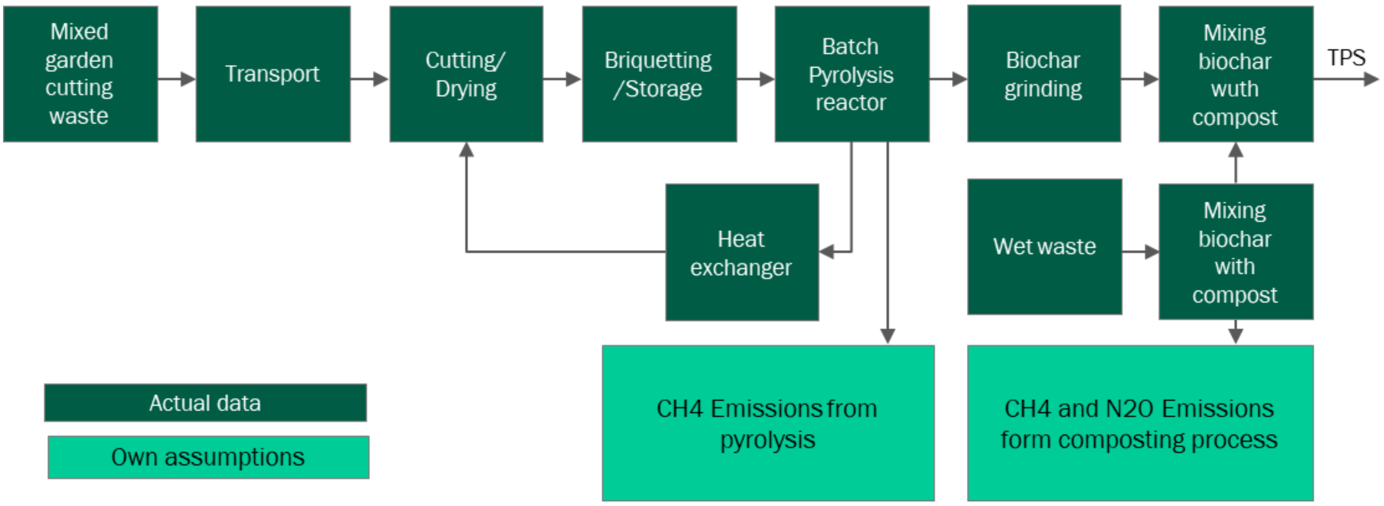

Figure 2 Concepts and involved processes for the production of biochar with the advanced approach (Virdarbha 5300 l)

Concept C: Biochar and Terra Preta substrate production with an automatised approach (CTS 40)

In this scenario, a continuously fed automatic or semi-automatic pyrolysis reactor is used. This allows utilising surplus heat from the pyrolysis to support the drying process. In contrast to concept B, there is no briquetting stage required. Instead, the shredded biomass is sieved, dried and fed directly into the pyrolysis reactor while composting the left-over dust fraction. The production pathway is shown in Figure 3.

The starting point for this concept is the segregation of mixed green waste into a woody fraction and leaves. The woody fraction is shredded mechanically by an electric shredder with an integrated sieving stage. The shredded and sieved biomass is dried in a drying drum.

After drying, the biomass is fed continuously into a single CTS 40 pyrolysis reactor with a capacity utilization of 63 %. Surplus heat is generated during the pyrolysis process that is partly used for the drying process and generates additional utilisable process heat.

The produced biochar is ground by an electric grinding device and mixed mechanically with wet semi-composted biogenic waste to produce Terra Preta Substrate with a biochar content of 20 %wt.

Finally, the produced Terra Preta Substrate can be distributed further for application in agricultural production systems.

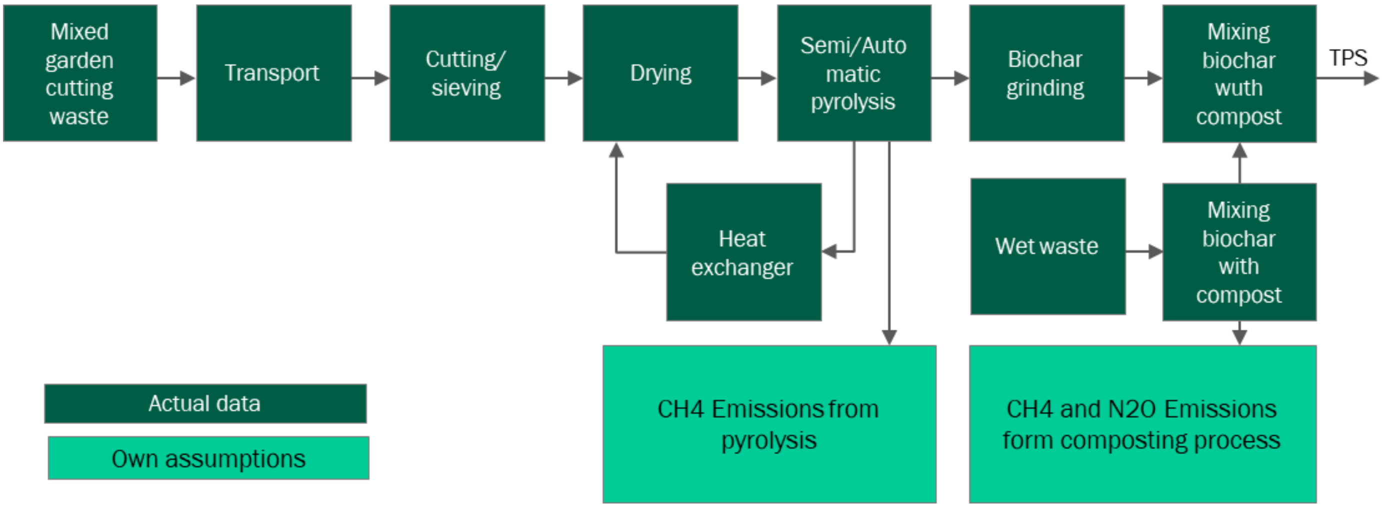

Figure 3 Concepts and involved processes for the production of biochar with an automatized approach (CTS 40)

Concept D: Biochar and Terra Preta substrate production with the 3R-System

The fourth concept is based on Concept C, with the difference that an alternative and more efficient pyrolysis reactor is used. The production pathway is shown in Figure 4.

The concept starts with a segregation of the mixed green waste into a woody fraction and leaves. The woody fraction is shredded mechanically by an electric shredder with an integrated sieving stage. The shredded and sieved biomass is dried in a drying drum. After drying, the biomass is fed continuously into a single 3R-Systems pyrolysis reactor with a capacity utilization of 45 %.

Surplus heat is generated during the pyrolysis process that is partly used for the drying process via heat exchangers and generates additional utilizable process heat.

The produced biochar is ground by an electric grinding device and mixed mechanically with wet semi-composted biogenic waste to produce Terra Preta Substrate with a biochar content of 20 %wt.

Finally, the produced Terra Preta substrate can be distributed further for application in agricultural production systems.

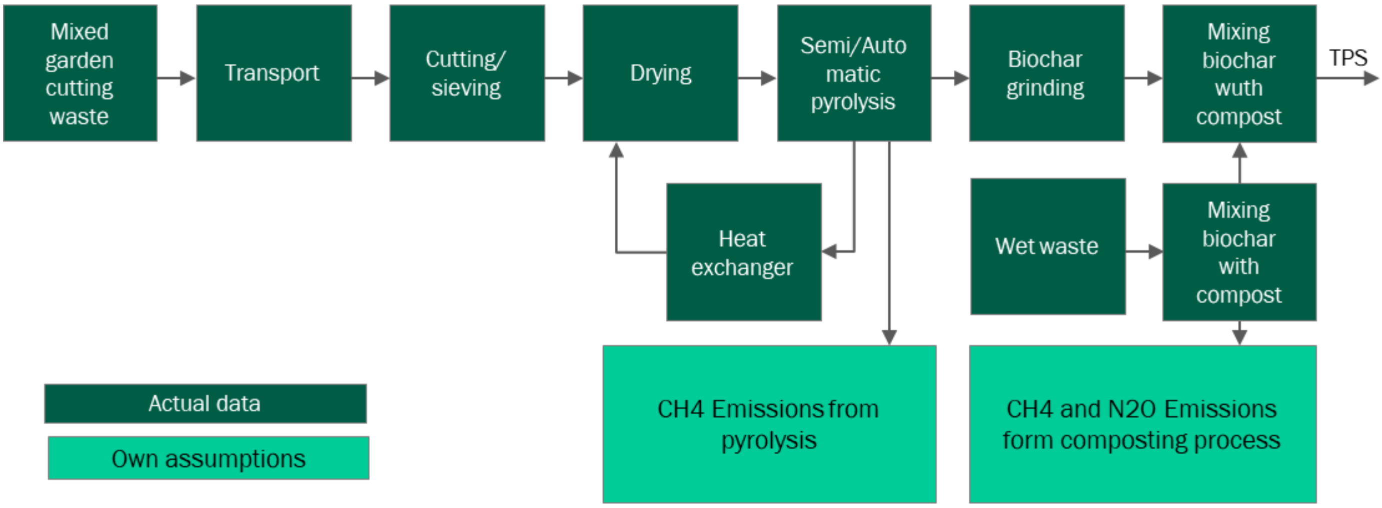

Figure 4 Concepts and involved processes for the production of biochar with the 3R-System

② Methodology and main specifications

In order to balance the emissions from the production of Terra Preta Substrates (TPS), a GHG balance was calculated on the basis of the life cycle assessment (LCA) methodology. This methodology is standardised in the international norms ISO 14040 and ISO 14044. According to the applicable standards, the assessment procedure includes four sub-steps (cf. Figure 5). Methodological decisions and specifications are necessary along these sub-steps. The essential points that are relevant for the assessment of the biochar production concepts are described in the following paragraphs.

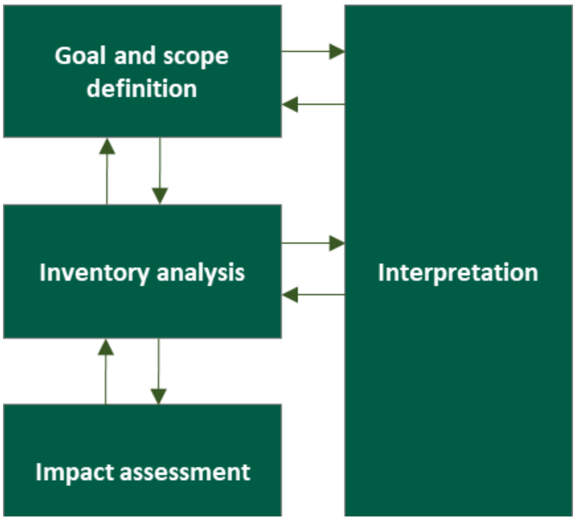

Figure 5 Life cycle assessment according to ISO 14040

Step 1: Goal and scope definition

System boundaries

In addition to the processes of biomass supply and pretreatment, pyrolysis, grinding, composting and Terra Preta substrate (TPS) production shown in Figure 1-4, the system boundaries of the GHG accounting also include the application of TPS in agriculture and associated perspective effects (cf. Figure 6). This essentially considers the transport of TPS to the agricultural site, the storage of carbon via the contained biochar and compost, and the provision of nutrients via the compost contained in TPS.

Functional unit

The functional unit is a unit of comparison that describes the benefit of the system. In this case, the benefit is the provision of TPS as a soil conditioner. One ton of TPS was chosen as the reference unit. All inputs and outputs as well as their effects are related to this reference value.

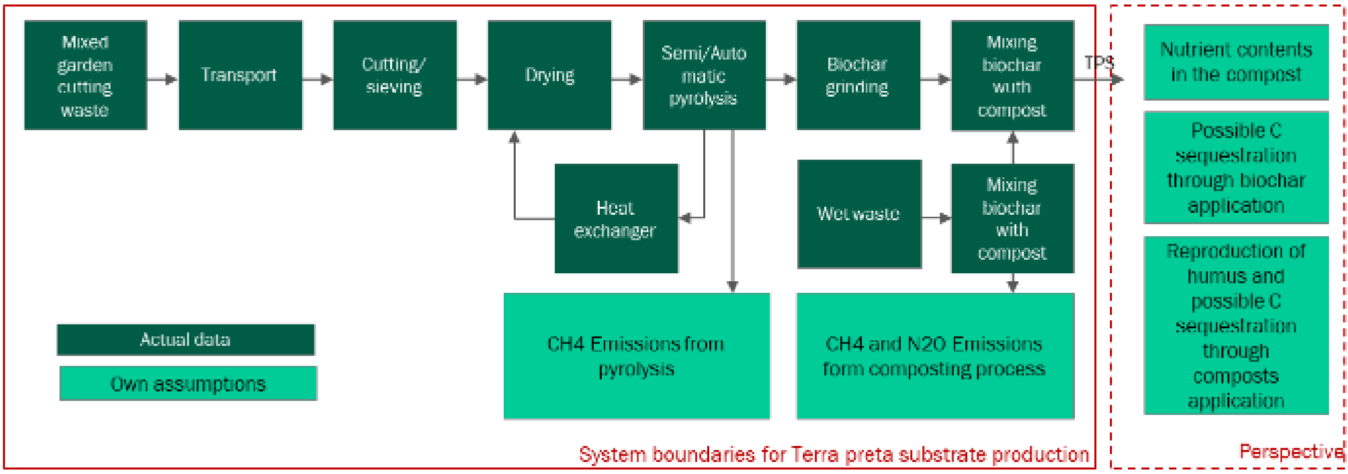

Figure 6 System boundaries

Credits[1]

The calculation focuses on the defined main product, 1 ton of Terra Preta as a substrate to improve soil quality. The additional benefits of TPS are, on the one hand, the sequestration of carbon through the application of biochar and compost, on the other hand, the provision of plant-available nutrients through the proportion of compost in the TPS and the associated substitution of synthetic fertiliser. There are different methods to allocate the associated environmental impacts proportionally to the main product (ISO 14040). In the present case, the credit method was chosen. In this approach, the emission savings from the additional benefits generated (e.g. avoided emissions from synthetic fertilizer substitution) are subtracted from the total emissions of the product system. By using the credit method, the impact of the additional benefit can be read directly in a bar chart.

Impact assessment

The present assessment of TPS production exclusively considers the impact category global warming potential (GWP). Within the GWP category, the relevant greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and dinitrogen oxide (N_2O). The global warming potential of greenhouse gases is expressed in kg of carbon dioxide equivalents (CO_2eq). To convert a given mass of methane to kg CO_2eq, the methane weight is multiplied by 28 and the nitrous oxide mass is multiplied by 265 (based on 100 years according to IPCC 2013) (Stocker et al. 2013).

Step 2: Inventory analysis- assumptions and input data

The life cycle inventory includes all inputs and outputs of the product system, including raw materials and materials, energy flows, water, and emissions to air, water, and soil. The following sections describe the databases and assumptions for calculating GHG emissions associated with TPS production.

The input data for the assessment was compiled from various data sources. The starting point for the data collection was a review of existing literature as well a data questionnaire, which was answered by local experts and GIZ staff and partners. Additionally, a local expert was introduced into the project as a subcontractor, helping to fill data gaps and verifying data points. Additionally, the set of available information was supplemented with data from research projects with comparable work content.

The following table summarises the main sources of input data for the individual sub-steps of the TPS process chain.

Table 2 Main sources of input data for the different process steps

Data sources	**Process step**						
	Transport and Preta-Treatment	**Pyrolysis**	**Grinding**	**Composting**	**Terra Preta Mixing**	**Transport**	**Application per ha**
Internal data collection sheet	X	X	X				
Ecoinvent Database	X		X	X		X	
DBFZ project Database				X	X		X
Tisserant & Cherubini, 2019							X
IPCC, 2016							X
Doussou, 2019							X

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[1] The concept of credits, as described in this section for the LCA, is not to be confused with the concept of carbon credit certificates, which aim to valorise emission reduction measures achieved by a project or a specific activity in another industrial sector.

In the categorisation of the data sources, a distinction must be made between information on the consumption of certain input materials (e.g. diesel), the direct emissions (e.g. from the combustion of the diesel) in the processes for providing the TPS and the upstream chain emissions from the provision of these input materials. While the information on the upstream chain emissions of the inputs used was mainly taken from the LCA database Ecoinvent, the data for consumption and direct emissions in the process steps considered were taken from the internal data collection sheet and the other data sources named in the Annex.

The main input data and assumptions for the assessment can be found in the annex of this document.

Transport

The distances of the transport of the biomass to the plant as well as the transport of the TPS to the agricultural area were provided via the data collection sheet. Transportation by tractor was assumed. The corresponding fuel and fuel consumption data are based on Swiss centre for life cycle inventories (2022).

Biomass pre-treatment (cutter, bundler, dryer)

The electricity demand for biomass pre-treatment processes mechanical cutting, briquetting (only Virdarbha 5300l concept) and biochar grinding as well as the diesel demand for the bundling process (Kon Tiki concept) are taken from the data collection sheet. The corresponding emission factors can be found in the annex in Table 3.

Pyrolysis and biochar treatment

Pyrolysis processes for the production of biochar can cause emissions of gases (mainly methane and carbon monoxide) and aerosols that are toxic and contribute to greenhouse gas emissions as well, this applies in particular to technologies and processes without treatment of the pyrolysis gases. For instance, in traditional earth mound or earth covered pit kilns, the pyrolysis gases are emitted unburned into the atmosphere generating significant gas emissions. And also, in simple drum kilns without gas recovery, unburned pyrolysis gases escape due to overpressure. In this cases Methane emissions in a range of 20-54 gCH_4/ kg biochar are expected (Al-Rumaihi et al. 2022; Cornelissen et al. 2016). This range was assumed for the concepts Kon Tiki (easy start) and Virdarbha (5300l).

For advanced technologies, where pyrolytic gases are recirculated in the combustion chamber and combusted internally a reduction of CH_4 emissions around 75% can be expected (range between 10-15 gCH_4/kg biochar) (Cornelissen et al. 2016; Sparrevik et al. 2015). A value of 12 $kgCH_4$/kg biochar was assumed for the concepts CTS and 3R. Indirect GHG gases from pyrolysis process like NO_x were not considered in this calculation

The preparation of the biochar in the form of grinding processes is operated by machine. The energy demand data for the electric-powered mill were also taken from the data collection sheet. The emission factor for the India-specific electricity mix were again taken from the Ecoinvent database (Annex Table 3).

Composting and mixing

Both the energy demand/electricity requirement (Annex Table 11) for the operation of the composting plant (turning, etc.) and the emission factor for the India-specific electricity mix was again taken from the Ecoinvent database (Annex Table 3).

Composting is one of the most feasible technologies for biogenic waste management, which allows recycling of organic nutrients and their reuse as fertilizers for cultivation processes. But during composting, greenhouse gases with a high GWP such as N_2O and CH_4 can be emitted due to organic degradation, in particular due to rapid degradation of nitrogenous organic matter and presence of anaerobic zones. The range of emissions considered in this study is taken from the DBFZ database as well as from Swiss centre for life cycle inventories (2010) and Swiss centre for life cycle inventories (2022). For the present calculation, an average value was used. The data are listed in Annex Table 11 and evaluated and discussed in the results chapter.

Biochar addition to compost can reduce CH_4 emissions due to (i) better aeration, (ii) reduced bulk density and gas diffusion (iii) creation of suitable conditions CH_4 consumers. But there is a wide range of the removal efficiency of CH_4 from 10% up to greater than 90% (Yin et al. 2021; Nguyen et al. 2022). Furthermore, biochar addition reduces the amount of inorganic nitrogen that can be utilized by nitrifying and denitrifying bacteria by capturing ammoniac and nitrate, thereby decreasing N_2O emissions. Emission reductions from 12% up to greater than 90% can be achieved by adding the biochar.

Due to the high uncertainties regarding the emissions from composting and the resulting reduction in GHG emissions from the addition of biochar, the reduction was not included in the calculation. Instead, without exact knowledge of the processes and circumstances, values from the lower value range were used for the calculation of the carbon emissions.

Calculation of credits for assumed carbon sequestration by application of biochar as substrate in Terra Preta

For the biochar contained in TPS, it is assumed that part of the carbon is present in a degradation-stable form. When Terra Preta substrate is used agriculturally as a soil conditioner, this portion of the carbon remains in the soil for a longer period of time. This means that the carbon sequestered during the growth of the plant is stored and thus removed from the atmosphere and can be accounted for by means of a CO_2 credit. In this context, the proportion of carbon in the biochar depends, among other things, on the biomass used in the pyrolysis process, and the proportion of carbon that is in turn in a stable form depends on the underlying pyrolysis temperatures. Based on the data from Dossou et al. (2019), Tisserant und Cherubini (2019) and IPCC (2019), the range for C-storage is 26-56 % based on the mass of biochar. For the calculation of GHG credits, the amount of degradable carbon is multiplied by the CO2-conversion factor of 3.67 gCO_2/g C. An average value was used for this calculation. The range of input data and resulting emission factors are listed in Annex Table 8 and are evaluated and discussed in the results chapter.

Humus reproduction potential and possible C sequestration through compost application

The organic substances contained in compost consist of easily degradable and humus-reproducing components. The easily degradable fractions of organic primary substances are used as a source of food and energy by heterotrophic soil organisms within a short period of time (usually in the year of application), and are thereby respired to form carbon dioxide. The humus-reproductive organic matter in the compost is metabolized into humus by the soil organisms and is then predominantly incorporated into the stabilized soil organic matter, which is only gradually degraded in subsequent years after the primary organic matter is applied. Thus, especially on humus-poor sites, compost application can be expected to result in significant humus enrichment, which is important for agricultural production (Reinhold 2008).

Compost applications in agriculture can make an important contribution to humus-C reproduction but it is not possible to reflect these benefits in the GHG balance without considering the years after application, regarding cultivation processes, yields and fertiliser use etc.

However, it is assumed (Smith et al. 2001) that a small proportion of the carbon applied with the compost is stored. Thus, for the application of composts in agriculture, the possibility of carbon storage (C sink) can also be considered. This approach is also used in Dehoust et al. 2010. For this purpose, 8% of the carbon bound in the compost is taken into account, for which it is assumed that it remains stored in the soil over a 100-year horizon. This means that the carbon sequestered during the plant's growth is stored and thus removed from the atmosphere and can be taken into account by means of a CO_2 credit. To calculate the GHG credits, the amount of decomposable carbon is multiplied by the CO_2 conversion factor of 3.6 gCO_2/g C.

So far, however, there have been no sufficiently long-term studies to prove that compost application in agriculture actually results in long-term carbon storage and thus contributes to climate protection. To show possible effects on the GHG balance, C storage through compost application was assumed despite the uncertainties. For the present calculation, an average value of the total carbon contents was used.

Calculation of credits for substituting industrial fertilisers with the nutrients contained in compost

The share of K_2O, P_2O5 and N nutrients included in the biochar which is available to plants can reduce the need for synthetic fertilisers. The resulting GHG credits are derived from the avoided expenses for the production and supply of the synthetic fertilisers. To calculate the credits, the amount of nutrients is multiplied by the emission factor of the corresponding fertiliser. The emission factors for the production of the synthetic fertilisers were taken from European Commission (2018) and are listed in Annex Table 3.

Step 3 and 4: Impact assessment and Interpretation

The following section describes the result of the GHG balance for the four concepts analysed.

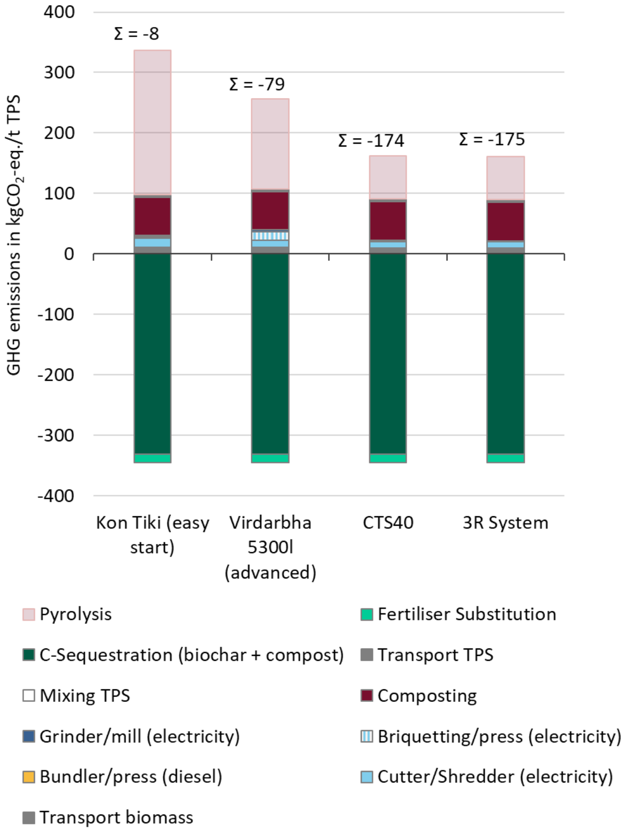

Figure 7 specific GHG emissions for the considered concepts in gCO₂-eq./t Terra Preta substrate (values Annex Table 12)

Overall, the results for the four analysed concepts show the largest differences in emissions from pyrolysis. According to the assumptions for pyrolysis emissions, a decrease in pyrolysis emissions with increasing technology advancements can be observed (from Kon Tki to 3R Systems).

Except for pyrolysis emissions, the results for the four concepts studied show very little difference in GHG emissions, both in terms of credits and emissions caused. The slightly higher emissions of the Virdarbha 5300l concept result mainly from the additional energy demand (electricity) for the briquetting process, which according to the data basis is only included in this concept pathway. Significant is the influence of the emissions from composting as well as the credits for carbon sequestration on the overall result across all concepts. A discussion of the main parameters influencing the overall GHG balance and the uncertainties in the presented results is given in the following chapters, taking the 3R systems concept as an example.

Detailed results and exemplary interpretation for 3R-systems

The results of the calculation of greenhouse gas emissions for concept 3R-systems are shown in the three diagrams in Figure 8 and are explained below:

- Graph (A): Emissions from the transport processes, pyrolysis, biochar preparation, and composting;
- Graph (B): Credits for carbon sequestration and synthetic fertilizer substitution;
- Graph (C): total and overall emissions.

Methane and nitrous oxide emissions from composting (represented by the red-coloured column segments) and methane emissions from pyrolysis process (pink transparent segment) have the largest impact on GHG emissions from Terra Preta Substrate (TPS) production (see Figure 8, graph (A)). Emissions from the use of fossil fuels and electricity for transportation and operational processes (blue and grey coloured segments) are rather small compared to direct composting and pyrolysis emissions.

The method described for evaluating GHG emissions allows for credits for the positive effects of C sequestration and nutrient addition. The values for the calculated credits are shown in Figure 8 graph (B). The credit for nutrient addition and associated synthetic fertiliser substitution totals -14 $kgCO_2eq/t$ TPS across all 3 fertiliser types. However, the credit for carbon storage accounts for by far the largest portion of the total credit at-304 $kgCO_2eq/t$.

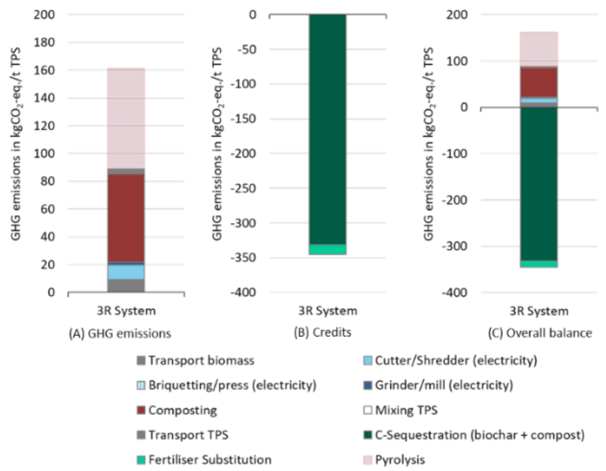

Figure 8 Results of GHG emissions calculation for A) emissions from transportation processes, biomass pre-treatment, pyrolysis, biochar processing, and composting; B) GHG credits for carbon sequestration and synthetic fertilizer substitution; C) sum and total emissions. (values Annex Table 12)

Total GHG emissions are calculated as the sum of emissions (Graph A) and credits issued (Graph B). The result is shown in the sum column in Figure 8, graph (C) and demonstrates the significant impact of the credits, particularly the credits for C-sequestration through the use of biochar and the GHG emissions avoided as a result, on the total emissions. The value of total emissions under the assumptions made is – 184 kgCO$_2$eq/t TPS. Some of main influencing factors and the uncertainties associated with the calculation are described and discussed in more detail in the following section.

Discussion of key influencing parameters and uncertainties in the present results

On the one hand, biochar can contribute to the improvement of soil functions (e.g. nutrient and water balance, soil reaction, binding of pollutants, yield capacity), especially in those soils that show corresponding deficits. On the other hand, pyrolysis-based biochar in particular can also enhance C-sequestration in soils due to its high stability. In this context, several factors influence the environmental performance or long-term stability of biochar application in agricultural soils. These include:

1. Soil and climatic conditions
2. Type of soil management
3. Production conditions during biomass conversion to biochar (gasification, pyrolysis).
    a. The organic carbon content of the biochar for each type of production and feedstock
    b. The proportion of biochar C remaining after 100 years, depending on temperature (range 65-89%) (IPCC 2019)

In particular, the latter two factors, the carbon content (dependent on conversion type and biomass type) and the fraction of stable C (dependent on temperature), result in a wide range for calculating the credit for carbon sequestration under the assumptions made. As shown in Figure 9, even with the assumed containment by assuming that pyrolysis biochar is based on herbaceous biomass (0.65±45% C content) (Dossou et al. 2019), the value for GHG credits can vary widely. Accurate knowledge of pyrolysis temperature could narrow the range of variation somewhat. An analysis of the corresponding parameters of the biochar is necessary for a higher certainty of the calculation results.

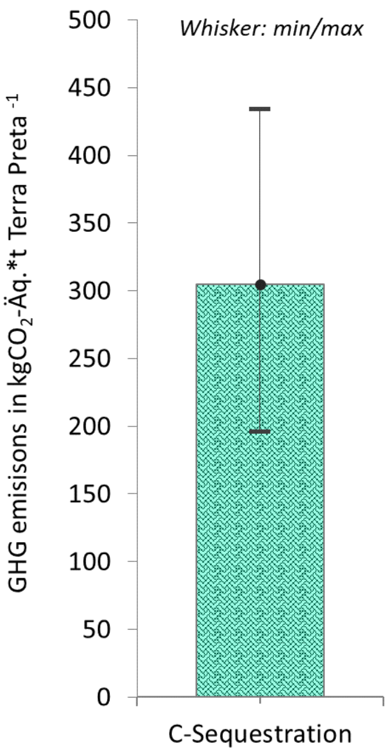

Figure 9 Possible range of GHG credit based on assumptions and uncertainties made

Range of direct GHG emissions from composting

The process design directly determines the level of emissions from the composting process. Environmental pollution can result from gaseous emissions, among other things. The amount and composition of the emitted gases depends on the rotting material and the rotting conditions. This essentially means that aeration and the composition of the compost material determine the emission of climate-relevant trace gases such as methane and nitrous oxide. If there is sufficient oxygen supply, e.g. by frequent turning of the compost heap, carbon dioxide formation dominates. If the oxygen supply is insufficient, methane formation sets in. Methane and nitrous oxide emissions from composting can strongly influence the total GHG emissions from TPS provision as shown in Figure 9. The uncertainty in the assumption of emissions is shown in the range presented in *Figure 10* from data from emission measurements. Under unfavourable rotting conditions, emissions can multiply as shown. However, for higher accuracy and certainty regarding climate-relevant emissions from composting, an analysis of the material to be composted and the existing composting conditions is needed, especially regarding the aeration of the compost heap.

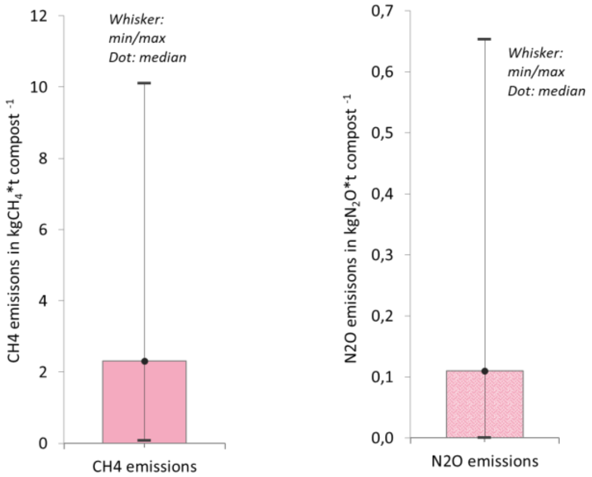

Figure 10 Possible ranges of emissions from composting as a result of uncertainties in input data. Left figure: Range of CH_4 emissions, Right figure: Bandwidth of N_2O emissions.

Range of nutrient levels in TPS due to the addition of compost

As already described, the nutrients contained in compost as part of TPS can replace synthetic fertilisers in agricultural applications. Since no specific data was available in this regard, literature values were again used here. The ranges for the amounts of the nutrients N, K_2O and P_2O_5, which depend primarily on the biomass to be composted, are shown in *Figure 11* and demonstrate the uncertainty in the application of the values, which in turn could be resolved by an appropriate analysis of the compost.

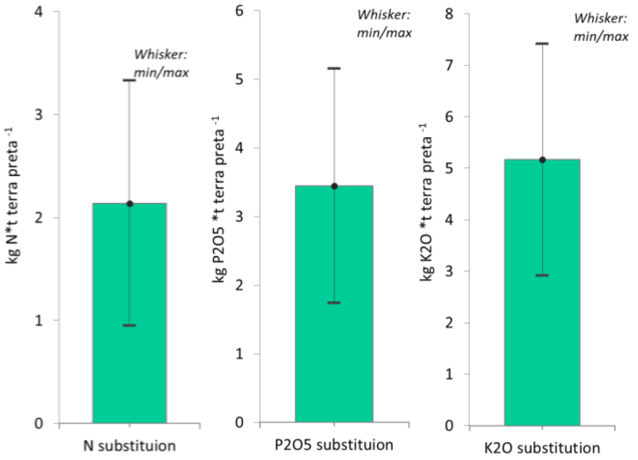

Figure 11 Possible ranges of nutrient contents for the balanced TPs

③ Discussion

The results of the analysis of GHG emissions for the four analysed concepts for Terra Preta Substrate (TPS) production identified the overall GHG emissions, the main contributors and drivers of emissions as well as the potential emission savings per ton of TPS.

For all concepts, the production and application of the TPS lead to negative emission results under the selected assumptions, resulting from an assumed carbon sequestration that exceeds the greenhouse gas emissions from the production of the TPS.

Whereby the concepts with advanced pyrolysis technology are the most advantageous due to the reduced CH_4 emissions from pyrolysis. According to the assumptions for pyrolysis emissions, a decrease in pyrolysis emissions with increasing technology progress can be observed (from Kon Tki to 3R Systems).

Emissions of methane and nitrous oxide from composting and pyrolysis process are by far the most significant emission sources in the overall result. Emissions from the use of fossil fuels and electricity, for example for the transport of biogenic feedstock, briquetting or grinding of the materials are rather secondary compared to direct composting emissions.

The result shows a high influence of carbon sequestration in the overall balance. The carbon introduced and permanently sequestered, mainly via the biochar, leads to a high credit for the amount of CO_2 sequestered during the growth of the biomass used and introduced into the soil via the biochar.

Biochar production and application to agricultural soils interact with the environment and climate system in multiple complex ways, this results in many uncertainties regarding:

- GHG emissions from Pyrolysis
- C-Sequestration
- Reduction of emissions from composting process by adding the biochar before composting

The same applies for composting process, a very complex decomposition process, depending on various parameters which results in a wide range of emissions.

From this follows that the main influencing factors in the overall result, the credit for C sequestration and the emissions from composting and pyrolysis are associated with high uncertainties. The literature shows high ranges of results for these parameters. In order to reduce these ranges in the future and to further increase the robustness of the accounting results, measurements of actual emission values or sequestered carbon should be taken regularly during the further implementation and operation of the investigated technologies in India.

These values can be integrated into the accounting and thus further increase the validity of the results.

In addition, except the emissions from pyrolysis, the results show slightly higher GHG emission values for concepts with a higher level of automation, mainly due to the relatively higher consumption of fossil energy carriers in these concepts. However, it has to be noted, that the respective concepts might be associated with other, additional benefits beside the reduction of emissions from pyrolysis, such as an increased overall production of total quantities of TPS.

Furthermore, the TPS produced provide nutrients which increase soil fertility and do thus provide a benefit in addition to increasing soil organic carbon. The effectiveness of the use of the contained nutrients or the carbon sequestration can be optimised by the management of the cultivation systems.

If the objective of using biochar and compost changes in the future, for example to sequester a higher proportion of carbon in the soil, it may make sense to adjust the ratios of biochar and composts for the production of Terra Preta Substrates.

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Annex

Table 3 Emission factors

			Unit	Value	Source	Element	X	Y	
Diesel			kgCO_2-eq./kg	3,14	Ecoinvent 3.9	A	100	50	
Electricity mix India			gCO_2-eq./kWh	1362	Ecoinvent 3.9	B	400	20	
N-fertiliser			kgCO_2-eq./kg	4,57	RED II				
K_2O-fertiliser			kgCO_2-eq./kg	0,417	RED II				
P_2O_5-fertiliser			kgCO_2-eq./kg	0,542	RED II				

Kon Tiki (Easy start)

Table 4 Input data Kon Tiki (Easy start)

Process		Transport	Cutter/ Shredder	Bundler/ Press	Dryer/ Container	Pyrolysis	Grinder Mill	Composting	Transport	Applikation
Input	Unit									
Mixed garden cuttings waste	TPD	47,7								
biogenic waste, woody fraction (moist)	TPD		29,7		25,65					
biogenic waste, leafs (to compost)	TPD		18							
biogenic waste, woody fraction (dry)	TPD					17				
Water	TPD					15				
Diesel demand	l/km	0,028								
Means of transport		Tractor							Tractor	
Distance	km	12							12	
Biochar	TPD					3,94		3,94		
Biochar grinded							3,94			
Manual										
Diesel demand	MJ/d			504						
Electricity	kWh/d		210		sun dry		21			
Input composting	TPD							29,7		
Compost	TPD									
Terra Preta Substrate	TPD								18,79	18,79

Output										
Waste, from cutting/shredding	TPD		1,35							
Biochar (20% wc)	TPD					3,94				
Biochar (20% wc) grinded							3,94			
Heat	kWh/d					2100				
Terra Preta Substrate	TPD							18,79		
CH4 compost	kg/d							40,84		
N2O compost	kg/d							1,70		
Terra preta substrat (1:3,77)	TPD									
N (available)	kg/t TPS									2,14
P_2O_5	kg/ t TPS									3,45
K_2O	kg/t TPS									4,91
C-Sequestration (biochar)	kg/t TPS									304,58
C-Sequestration (compost)	kg/ t TPS									26,9

Virdarbha 5300l (Advanced)

Table 5 Input data Virdarbha 5300l (Advanced)

Process		Transport	Cutter/ Shredder	Dryer/ Container	Briquetting Press	Pyrolysis	Grinder Mill	Composting	Transport	Applikation
Input	Unit									
Mixed garden cuttings waste	TPD	54,18								
biogenic waste, woody fraction (moist)	TPD		36,18							
biogenic waste, leafs (to compost)	TPD		18							
biogenic waste, woody fraction (dry)	TPD			25,65	17	17				
Water	TPD					5				
Diesel demand	l/km	0,028								
Means of transport		Tractor							Tractor	
Distance	km	12							12	
Biochar	TPD						4,72	4,72		
Biochar grinded	TPD									
Terra preta substrate (20% biochar))	TPD									
Manual										
Heat demand	kwh/d			From pyrolysis						
Electricity demand	kWh/d		210		245		42			
Input composting	TPD							36,18		
Compost	TPD									
Terra Preta Substrate	TPD								22,81	22,81
Output										
Waste, from cutting/shredding	TPD		1,35							
Biochar (20% wc)	TPD					4,72				
Biochar (20% wc) grinded							4,72			
Heat	kWh/d					1400				
Terra Preta Substrate	TPD							22,81		
CH_4 compost	kg/d							49,75		
N_2O compost	kg/d							2,07		
Terra preta substrate (1:3,77)	TPD									
N (available)	kg/t TPS									2,14
P_2O_5	kg/ t TPS									3,45
K_2O	kg/t TPS									4,91
C-Sequestration (biochar)	kg/t TPS									304,58
C-Sequestration (compost)	kg/ t TPS									26,9

CTS 40 (Automatic)

Table 6 Input data

Process		Transport	Cutter/ Shredder	Dryer/ Container	Pyrolysis	Grinder Mill	Composting	Transport	Applikation
Input	Unit								
Mixed garden cuttings waste	TPD	54,18							
Mixed garden cuttings waste	TPD	57,81							
biogenic waste, woody fraction (moist)	TPD		39,81						
biogenic waste, leafs (to compost)	TPD		18						
biogenic waste, woody fraction (dry)	TPD			25,65	17				
Water	TPD				5				
Diesel fuel	l/km	0,028							
Means of transport		Tractor						Tractor	
Distance	km	12						12	
Biochar	kg					5,196	5,196		
Heat demand	kWh/d			From pyrolysis					
Electricity demand	kWh/d		210			42			
Input composting	TPD						39,81		
Compost	TPD								
TPS	TPD							25,101	25,101
Output									
Waste, from cutting/shredding	TPD		1,35						
Biochar (20% wc)	TPD				5,196				
Biochar (20% wc) grinded						5,196			
Heat	kWh/d				5250				
Compost	TPD						25,101		
CH_4 compost	kg/d						54,74		
N2O compost	kg/d						2,28		
Terra preta substrat (1:3,77)	TPD								
N (available)	kg/t TPS								2,14
P_2O_5	kg/ t TPS								3,45
K_2O	kg/t TPS								4,91
C-Sequestration (biochar)	kg/t TPS								304,58
C-Sequestration (compost)	kg/ t TPS								26,9

3R-Systems (Automatic)

Table 7 Input data 3R-Systems (Automatic)

Process		Transport	Cutter/ Shredder	Dryer/ Container	Pyrolysis	Grinder Mill	Composting	Transport	Applikation
Input	Unit								
Mixed garden cuttings waste	TPD	59							
biogenic waste, woody fraction (moist)	TPD		41						
biogenic waste, leafs (to compost)	TPD		18						
biogenic waste, woody fraction (dry)	TPD			25,65	17				
Water	TPD				5				
Diesel demand	l/km	0,028							
Means of transport		Tractor						Tractor	
Distance	km	12						12	
Biochar	kg					5,356	5,356		
Biochar grinded									
Heat demand	kWh/d			From pyrolysis					
Electricity demand	kWh/d		210			42			
Input composting	TPD						41		
Compost	TPD								
TPS	kg							25,856	25,856
Output									
Waste, from cutting/shredding	TPD		1,35						
Biochar (20% wc)	TPD				5,356				
Biochar (20% wc) grinded						5,356			
Heat	kWh/d				10500				
Compost	TPD						25,856		
CH_4 compost	kg/d						56,38		
N2O compost	kg/d						2,35		
Terra preta substrat (1:3,77)	TPD								
N (available)	kg/t TPS								2,14
P_2O_5	kg/ t TPS								3,45
K_2O	kg/t TPS								4,91
C-Sequestration (biochar)	kg/t TPS								304,58
C-Sequestration (compost)	kg/ t TPS								26,9

Table 8 Input data and range C-sequestration (biochar)

Biochar				
	min	max	Source	**MW**
C-content in %	43%	71%	[3]	**57%**
Resilient C	60%	80%	[4]	**70%**
Conversion C into Co2	3,67			
CO_2 sequestration per kg biochar	0,95	2,08		**1,46**
CO_2 sequestration per t terra preta	196,95	433,59		**304,58**

Table 9 Input data and range C-sequestration (compost)

Compost				
	min	max	Source	**MW**
Humus C-kg/t	56,00	67,00	[5]	**59,00**
C org bei 51% Humus C	109,80	131,37	[11]	**115,69**
Stabil C ca. 8% von C org	8,78	10,51	[12]	**9,25**
Conversion C into Co2	3,67	3,67		**3,67**
kg CO_2 sequestration per t compost	32,24	38,57		**33,97**
kg CO_2 sequestration per t terra preta	25,53	30,55		**26,90**

Table 10 Input data and range nutrient content and fertiliser substitution

Nutrient content and fertiliser substitution				
	min	max	Source	**Average**
N (available) kg/tFM	1,2	4,2	[5]	**2,7**
P_2O_5 kg/tFM	2,2	6,5	[5]	**4,35**
K_2O kg/tFM	3,5	8,9	[5]	**6,2**
N- available in kg per t terra preta			[5]	**2,14**
P_2O_5 in kg per t terra preta			[5]	**3,45**
K_2O in kg per t terra preta			[5]	**4,91**

Table 11 Input data and range energy demand and emissions from composting

Composting					
Source		MW	min	max	**Median**
Input	Unit				
Biomass (ratio 2:1)	kg	2	2	2	**2**
Diesel	MJ	0,12	0,00	0,18	**0,16**
Electricity	kWh	0,0035	0,0000	0,0078	**0,0018**
Output					
Compost	kg	1	1	1	**1**
CH_4	kg	0,00464	0,00008	0,01010	**0,00275**
N_2O	kg	0,00018	0,00000	0,00065	**0,00011**

Results

Table 12 Results specific GHG emissions for the considered concepts in gCO_2-eq./t TPS

Process	Kon Tiki (easy start)	Virdarbha 5300l (advanced)	CTS40	3R System
Transport biomass	11,31	10,55	9,59	9,31
Cutter/Shredder (electricity)	14,81	12,20	11,09	10,30
Bundler/press (diesel)	2,48			
Dryer (electricity)		10,17	9,24	8,97
Briquetting/press (electricity)		14,23		
Pyrolysis (CH4 emissions)	239,00	149,00	71,70	71,70
Grinder/mill (electricity)	1,48	2,44	2,22	2,15
Composting (CH_4 + N2O)	63,23	63,23	63,23	63,23
Transport TPS	4,46	4,46	4,46	4,46
C-Sequestration (biochar + compost)	-331,48	-331,48	-331,48	-331,48
Fertiliser Substitution	-13,70	-13,70	-13,70	-13,70
Sum	**-8**	**-79**	**-174**	**-175**

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