Zenodo (December 2024)
DOI: 10.5281/zenodo.19785243

Advancing Waste-to-X Technologies: Sustainable Thermochemical Pathways for Biomass Valorization and Carbon Credit Potential

Ahmad Saylam

Independent Researcher – Applied Physical and Chemical Sciences
Duisburg, Germany
Corresponding author: saylamah@gmail.com

Abstract

As the global demand for sustainable waste treatment technologies grows, energy, syngas, and biochar production from waste emerges as a promising solution to mitigate climate change. This study explores the potential of carbon credits and environmental sustainability for biochar production through various thermochemical treatment approaches of wood as a representative waste type. Three distinct cases are evaluated: Case 1, involving traditional pyrolysis with syngas post-combustion; Case 2, incorporating partial syngas combustion; and Case 3, utilizing renewable energy-powered hot "inert" (non-oxidizing) gases.

The results demonstrate that Case 1, despite producing biochar, falls short in terms of sustainability due to high CO_2 and NO_x emissions during the syngas combustion phase, which counteract the carbon sequestration benefits of biochar and disqualify it from carbon credit eligibility. In contrast, Case 2 offers a practical intermediate solution by reducing emissions and improving energy efficiency while producing valuable syngas for biofuel and chemical production. Case 3 represents the most sustainable option, utilizing hot inert gases from renewable sources such as solar or wind energy and releasing no CO_2 or NO_x, thus offering a zero-emission solution. By integrating syngas reforming and renewable energy, both Case 2 and Case 3 significantly enhance the potential for carbon credit generation and align with circular economy principles.

However, it is crucial to consider not only the CO_2 emissions directly generated by the core thermochemical and chemical processes in Waste-to-X conversion, reforming, and recycling but also the emissions associated with producing the chemicals and materials required for these operations. Addressing these indirect contributions is vital to accurately evaluate the full carbon credit potential of Waste-to-X solutions and to ensure they deliver meaningful climate benefits.

This study underscores the importance of adopting advanced, holistic approaches to achieve authentic carbon-neutral biochar production, thereby contributing to climate change mitigation, enhancing resource efficiency, and offering strong economic incentives for sustainable and clean climate technologies.

Keywords: Waste, Biomass, Recycling, Pyrolysis, Credit Potential, Biochar, Syngas.

Introduction

The world is increasingly seeking ways to reduce greenhouse gas emissions and transition toward sustainable energy solutions. Waste-to-X (WtX) technologies have emerged as a versatile and promising approach, converting various waste materials into valuable outputs such as energy, fuels, chemicals, and materials. These processes encompass a broad spectrum of waste types, including biomass, plastics, municipal solid waste, and industrial by-products. By generating renewable energy, such as electricity or heat, and avoiding methane emissions from the anaerobic decomposition of organic waste, WtX facilities contribute to climate mitigation efforts and the circular economy. However, the environmental benefits of WtX solutions are contingent upon minimizing emissions, including CO_2 and pollutants such as dioxins or particulate matter, which can arise during the conversion processes.

This study narrows its focus to thermochemical treatment technologies for biomass, particularly wood waste, one of the most abundant and underutilized resources. These technologies, such as pyrolysis, gasification, and hydrothermal carbonization, are widely used for converting biomass into biochar, syngas, and bio-oil. Biochar, produced via the pyrolysis of wood waste, is particularly notable for its dual role in carbon sequestration and energy generation. Its ability to store carbon for extended periods makes it a key component in long-term climate change mitigation strategies.

However, traditional methods of biochar production are often associated with significant emissions, particularly CO_2 and NO_x, during the syngas combustion phase. To overcome these challenges, recent advancements have focused on integrating renewable energy sources and implementing innovative process designs that not only minimize emissions but also enhance overall process efficiency. Beyond biomass, these principles can be extended to plastics and other waste materials, enabling their conversion and recycling into valuable chemical building blocks, fuels, and other products.

Case Study of the Three Thermochemical Treatment Cases

This work evaluates three thermochemical treatment scenarios for wood waste, comparing their carbon credit potential and sustainability outcomes. By exploring these cases, it highlights some opportunities and challenges in achieving cleaner, more efficient WtX processes and underscores the importance of holistic approaches in the transition to a sustainable future:

- **Case 1:** Traditional adopted treatment involving drying, pyrolysis, and post-combustion of syngas to generate heat.
- **Case 2:** Adjusted treatment with partial combustion of syngas to supply energy for drying and pyrolysis, while reducing emissions.
- **Case 3:** Adjusted treatment using hot inert gases driven by renewable energy, eliminating the need for combustion and minimizing emissions.

We analyze the credibility of carbon credits generated by these processes, emphasizing the potential for CO_2 neutral production and carbon offsetting that these technologies can offer.

Each of the three cases represents a different approach to wood waste treatment, each with distinct environmental implications. Below, we provide a comparison based on key parameters: emissions, energy efficiency, and carbon credit potential.

Results and Discussion

The following study compares the emissions and production of the three thermochemical treatment scenarios for processing 100 kg/h of wood waste under the following general conditions:

- **Pyrolysis temperature**: 700-800°C (this will typically enhance the degradation of lignocellulosic material, leading to higher syngas yields and lower biochar yields compared to lower pyrolysis temperatures).
- **Wood composition**: Assuming a typical wood composition of 50% carbon, 6% hydrogen, 44% oxygen for dry matter, and 15% moisture content in the feedstock.

Parameter	Case 1 Full Combustion	Case 2 Partial Combustion	Case 3 No Combustion (External Renewable Energy)
Wood Waste Input	100 kg/h		
Moisture Content	15%		
Dry Wood Input	85 kg/h		
Biochar Production	25 - 30 kg/h		
Ash Production	1 - 2 kg/h		
Syngas Composition*	CO: 20-40%, CO_2: 15-30%, H_2: 15-25%, CH_4: 5-15%, C_2H_4+others: 1-5%		
Syngas Production	0	34-38 kg/h	50-55 kg/h
CO_2 Emissions	40.5-57.6 kg/h	20.3-28.7 kg/h	0 kg/h
NOx Emissions	0.17-0.19 kg/h	0.09-0.1 kg/h	0 kg/h

*Syngas composition of Case 3.

Case 1: Normal Treatment (Drying, Pyrolysis, and Post-Combustion)

In this conventional approach, wood waste undergoes drying, followed by pyrolysis at temperatures between 700-800°C. The syngas produced during pyrolysis is then combusted to provide heat. This case generates significant CO_2 and NOx emissions, as the syngas combustion process releases large amounts of carbon dioxide and nitrogen oxides into the atmosphere.

- **Emissions**: High CO_2 and NOx emissions due to post-combustion.
- **Energy Efficiency**: The system is energy self-sufficient, utilizing syngas combustion to meet its own thermal needs, as well as it produces excess heat energy, which can be utilized for other processes.
- **Carbon Credit Potential**: Limited, as the high emissions undermine the carbon neutrality of the process.

Case 2: Adjusted Treatment with Partial Syngas Combustion

This case improves upon Case 1 by using partial combustion of syngas to generate just enough heat for the drying and pyrolysis stages. This approach reduces the overall emissions by controlling the combustion process more carefully, resulting in a reduction in CO_2 and NOx emissions compared to Case 1.

- **Emissions**: Reduced CO_2 and NOx emissions due to controlled combustion.
- **Energy Efficiency**: The system is energy self-sufficient, utilizing adjusted syngas combustion to meet its own thermal needs, with reduced emissions and a more optimized energy cycle.
- **Carbon Credit Potential**: Higher potential for carbon credits compared to Case 1, as the reduced emissions increase the overall sustainability of the process.

Case 3: Adjusted Treatment with Hot inert Gases and Renewable Energy

In this most sustainable approach, no combustion occurs. Instead, hot inert gases sourced from renewable energy (such as solar or wind) are used to drive the pyrolysis process. This eliminates CO_2 and NOx emissions entirely, making this method the most environmentally friendly.

- **Emissions**: Virtually no CO_2 or NOx emissions due to the absence of combustion.
- **Energy Efficiency**: Highly energy-efficient, as renewable energy powers the process, ensuring that the entire treatment is sustainable.
- **Carbon Credit Potential**: The highest potential for carbon credits, as the process is carbon-neutral and has the lowest environmental impact.

In Cases 2 and 3, It could be noticed that the focus is on minimizing emissions from combustion and reforming syngas for producing biofuels and chemicals through sustainable and clean processes.

Key Advantages of Cases 2 and 3 in Biochar Production:

1. Emission Control and Carbon Neutrality in Case 2:

- **Controlled Syngas Combustion**:
  - In Case 2, instead of fully combusting the produced syngas to generate heat, only a partial combustion is applied. This approach allows for more controlled emissions of CO_2 and NOx, thereby lowering the overall emissions compared to full combustion.
  - By using the syngas produced during pyrolysis for self-sustaining heat generation, the carbon neutrality of the system improves, as the CO_2 released from partial combustion can be considered part of the carbon cycle, with biomass being a renewable source.

- **Production of Renewable Energy**:
  - Syngas is typically a mixture of carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2), and other trace gases, all of which can be reformed and utilized to produce renewable biofuels and chemicals.
  - A partial combustion ensures that enough heat is available for the drying and pyrolysis processes without generating excessive pollutants.
- **Minimization of Greenhouse Gases**:
  - Compared to Case 1, where full combustion might lead to higher emissions of NOx, CO_2, and particulate matter, Case 2 reduces NOx emissions due to the careful control of combustion temperature, and optimizes heat production for the pyrolysis process with lower emissions.
- **Integration of Carbon Capture (Optional)**:
  - In this case, a carbon capture mechanism (e.g., carbon capture and storage (CCS) or carbon capture and utilization (CCU)) can be added to further reduce CO_2 emissions, adding another layer of sustainability.

2. Zero Emission Potential in Case 3 (Hot Inert Gas Process):

- **No Combustion, Zero CO_2 & NOx Emissions**:
  - In Case 3, no combustion is involved, meaning no CO_2 or NOx emissions are generated from the process. Instead, the pyrolysis process is driven by hot inert gases obtained from renewable energy sources such as solar, wind, or biogas.
  - This leads to a completely emissions-free process, which is a significant advantage when considering carbon credits. The absence of CO_2 and NOx emissions makes this case highly favorable for projects seeking to mitigate climate change through clean energy and sustainable production methods.
- **Renewable Energy Integration**:
  - Hot inert (non-oxidizing) gases supply the thermal energy required for pyrolysis. These gases can be fully or partially generated during the pyrolysis stage or sourced from renewable energy systems, such as solar thermal energy, biogas, or wind energy.
  - This enables a 100% renewable process, which avoids the need for burning fossil fuels and significantly reduces the carbon footprint of the process.
- **Circular Economy Model**:
  - The use of hot inert gases and avoiding combustion aligns with the circular economy model, where energy is continuously recirculated in the system, and only minimal amounts of waste (i.e., biochar) are produced.
  - In this case, the produced biochar still captures significant carbon from the biomass, contributing to long-term carbon sequestration.

3. Post-Reforming of Syngas: Biofuel and Chemical Production without CO_2 and NOx Emissions

Both Case 2 and Case 3 can benefit from syngas reforming to produce biofuels and chemicals in a clean and sustainable manner. Here’s how:

- **Syngas Reforming Process:** The syngas produced during pyrolysis (whether from partial combustion, or from Case 3 where no combustion is involved) can be reformed to produce biofuels (e.g., bioethanol, biobutanol) or chemicals (e.g., methanol, acetic acid, and other valuable chemicals). These fuels and chemicals can be used in sustainable energy systems or serve as building blocks for further chemical manufacturing.
- **Cleaner Chemical Synthesis:** Syngas reforming for biofuel and chemical production results in a much cleaner process with no direct CO_2 or NOx emissions if managed properly. Since the reforming occurs at elevated temperatures and can be fueled by renewable energy, it avoids the pollutants typically produced by traditional chemical synthesis processes that rely on fossil fuels.
- **Energy Balance and Efficiency:** The energy produced from syngas reforming can be used to sustain the pyrolysis or drying process (in Case 2), leading to an energy-efficient closed-loop system. As well as, the syngas-to-biofuel conversion can further supply sustainable biofuels to be used as transportation fuels or in power generation, contributing to the decarbonization of various sectors (transportation, industry, power).

4. Carbon Credit Potential for Cases 2 and 3 (with Syngas Reforming):

Both Cases 2 and 3 provide favorable conditions for generating carbon credits:

- **Emissions Reduction:** By minimizing or eliminating the direct release of CO_2, NOx, and other pollutants, these cases would generate significant emission reductions compared to traditional waste treatment methods like incineration or landfill.
- **Biofuel and Biochar as Renewable Products:** The production of biofuels and biochar contributes to carbon-neutral energy systems, which qualify for carbon credits. The biochar component sequesters carbon for the long term, while the biofuels contribute to carbon-neutral energy systems that replace fossil fuels.
- **Closed-Loop Carbon Cycle:** Since the syngas can be reformed and utilized without generating additional CO_2 or NOx, the overall carbon emissions from the system are kept low, contributing to an overall reduction in greenhouse gases.
- **Carbon Credits from Renewable Energy:** If the hot inert gases used in Case 3 come from renewable sources, additional carbon credits can be obtained for the renewable energy used to power the pyrolysis process, further increasing the potential for credits.

5. Syngas Storage and External Reforming

If the syngas production rate is not large enough to justify on-site reforming or power generation, it can be stored and then sold to specialized syngas reforming plants.

Syngas Storage Considerations:

- **Storage Feasibility**: The cost of storing syngas depends on its composition and the type of storage used (compressed gas, liquefied gas, or as part of a chemical process).
  - **Storage conditions**: Syngas can be stored at high pressure in tanks, or in liquid form at very low temperatures, but this requires considerable investment in storage infrastructure.

- **Storage Duration**: Syngas should be stored at minimal pressure and for short periods (weeks or months) to avoid degradation or contamination.

Production Rate and Syngas Storage:

1. **Low Syngas Production (<50 Nm^3/h)**: For low syngas production rates, storing the syngas might not be practical or profitable, and it might be better to sell the syngas directly to a larger reforming plant for further processing.
2. **Moderate Syngas Production (50-100 Nm^3/h)**: For this range, you could consider storing the syngas if there is limited immediate demand and ship it to specialized reforming facilities on demand. Alternatively, if your plant produces syngas consistently, you can negotiate contracts with larger plants for regular syngas supply.
3. **High Syngas Production (>100 Nm^3/h)**: If your plant produces more than 100 Nm^3/h, it's more efficient to either add a reforming unit on-site or negotiate long-term supply contracts with large-scale reforming plants that can handle the volumes, especially if you are focusing on producing valuable products like hydrogen or methanol.

Conclusion

As the global demand for sustainable waste treatment technologies continues to grow, biochar production from wood waste, as a representative waste type, presents a promising approach to mitigating climate change. This study evaluated three distinct thermochemical treatment methods for wood waste, focusing on their potential for carbon credit generation and environmental sustainability. These cases aim to mitigate the environmental impact associated with traditional wood waste treatment processes and provide a pathway to carbon-neutral production:

- **Case 1:** The traditional wood waste treatment process involving full syngas combustion, while providing a solution for biochar production, falls short in terms of sustainability due to high emissions and limited carbon credit potential.
- **Case 2:** With partial syngas combustion, this case offers a balanced approach, reducing emissions and improving energy efficiency while still producing valuable syngas for biofuel and chemical production.
- **Case 3:** Utilizing hot inert gases powered by renewable energy, this case presents the most sustainable approach by minimizing emissions and enhancing energy efficiency.

In the conventional approach to wood waste treatment, Case 1—drying, pyrolysis, and post-combustion of syngas—presents several challenges in terms of carbon credit generation. While biochar production through pyrolysis offers potential for carbon sequestration, the emissions produced during the syngas combustion phase significantly undermine the environmental benefits of the process. This phase releases high levels of CO_2 and NO_x, contributing to greenhouse gas emissions rather than mitigating them. As a result, Case 1 does not fully align with the principles of carbon neutrality or carbon credit generation. The high emissions produced during the post-combustion phase disqualify this method from being eligible for meaningful carbon credit generation, which is an essential mechanism for promoting sustainable practices in the fight against climate change. Carbon credits are typically awarded for processes that lead to significant emission reductions and carbon sequestration.

Adopting Cases 2 and 3 for biochar production, especially with syngas reforming, is a highly promising approach for achieving higher carbon credits and contributing to climate change mitigation. Here's why:

- **Case 2** (with controlled syngas combustion) allows for lower emissions of CO_2 and NO_x, generating heat and syngas that can be used to produce biofuels and chemicals. This dual benefit of energy recovery and reduced emissions makes it a practical intermediate solution.
- **Case 3** (with no combustion and using hot inert gases from renewable sources such as solar or wind energy) represents a zero-emission process with no CO_2 or NO_x released. This makes it the most sustainable option for biochar production. Additionally, integrating syngas reforming for biofuel and chemical production adds further value by generating renewable energy products without the environmental impact of traditional fossil-fuel-based processes.

Both cases align with the principles of a circular economy and sustainable energy systems. However, it is crucial to consider the CO_2 production associated not only with the primary thermochemical and chemical processes involved in converting, reforming, and recycling Waste-to-X but also with the upstream production of the necessary chemicals and materials used in these processes. The overall carbon credit potential of a Waste-to-X (WtX) solution must account for these indirect emissions to ensure that the entire process achieves genuine and significant carbon credit generation.

Economic Feasibility and Scalability

For syngas reforming, economic viability typically requires a production rate exceeding 50–100 Nm^3/h. Below this threshold, syngas should generally be sold to third-party specialized plants for reforming or other uses. This highlights the need for carefully scaling facilities to maximize both environmental and economic benefits. While Case 3 represents the gold standard in sustainability, its implementation may require higher initial investment due to the reliance on renewable energy and advanced technology. Nevertheless, the long-term gains in carbon credit generation and environmental impact reduction make it an attractive option for large-scale adoption.

By embracing innovative approaches like Cases 2 and 3, waste-to-X (WtX) facilities can play a pivotal role in transitioning towards a sustainable and carbon-neutral future. These methods not only reduce greenhouse gas emissions but also foster resource efficiency and resilience within industrial and agricultural systems.

References

1. Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for Environmental Management: Science, Technology and Implementation*. Routledge.
2. Bridgwater, A. V. (2012). "Review of fast pyrolysis of biomass and product upgrading." *Biomass and Bioenergy, 38*, 68-94.

3. Antal, M. J., & Grønli, M. (2003). "The art, science, and technology of charcoal production." *Industrial & Engineering Chemistry Research, 42*(8), 1619-1640.
4. Balat, M., Balat, M., & Kirtay, E. (2009). "Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 1: Pyrolysis systems." *Energy Conversion and Management, 50*(12), 3147-3157.
5. Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). "Sustainable biochar to mitigate global climate change." *Nature Communications, 1*(56).
6. Shen, Y., Zhao, P., Shao, Q., Takahashi, F., & Yoshikawa, K. (2014). "In-depth investigation of biomass pyrolysis based on three major components: Hemicellulose, cellulose, and lignin." *Applied Energy, 131*, 70-75.
7. Liu, C., Wang, H., Karim, A. M., Sun, J., & Wang, Y. (2014). "Catalytic fast pyrolysis of lignocellulosic biomass." *Chemical Society Reviews, 43*(22), 7594-7623.
8. Schimmel, M., Van der Drift, A., & Kersten, S. R. A. (2020). "Biomass gasification for a circular economy: Review of recent developments in optimization strategies and process analysis." *Renewable & Sustainable Energy Reviews, 124*, 109788.
9. Azzi, E. S., Karltun, E., & Sundberg, C. (2019). "Biochar systems for smallholders in developing countries: Leveraging food security and sustainable energy." *Renewable & Sustainable Energy Reviews, 104*, 503-515.
10. IPCC (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*.