

Mass Balance, Yield, and Carbon-Credit Economics of Biochar from Certified Wood Pellets: A Single-Batch Tube-in-Tube Pyrolysis Snapshot

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Abstract

A single, fully mass-balanced batch of biochar was produced from ENplus A1 certified wood pellets (Austrian softwood, predominantly fir/spruce) in a small, externally fired tube-in-tube reactor operated under oxygen-limited conditions for 40 min. The endpoint was defined operationally by the cessation of wood-vinegar (pyroligneous) condensation. From 349.5 g of as-received pellets, the batch yielded 97.3 g of solid biochar, 114.8 g of condensed wood vinegar, and 137.4 g of non-condensable gas plus minor system losses by difference (39.3 % of input mass). The biochar yield was 27.8 % on an as-received basis and 30.3 % on a dry basis, in the upper half of the 20-35 % range typical of slow pyrolysis. The char bulk density was 324 kg m^{-3} , roughly half the feedstock pellet density ($600\text{--}750 \text{ kg m}^{-3}$), corresponding to a 72 % mass reduction and a substantial gain in porosity. The non-condensable off-gas (pyrogas) was tested and found to be non-combustible, consistent with the low calorific value of wood-derived producer gas. A raw-material cost analysis, including external firing fuel, gives a production cost of approximately EUR 7.29 per kg of biochar and an implied carbon-removal cost of approximately EUR 3,540 per tonne CO_2 -equivalent. Benchmarked against the May 2026 EU Emissions Trading System allowance price ($\sim$ EUR 74-75 per tonne CO_2), this batch is $\sim$ 45x too costly to break even; even under idealized autothermal operation the gap remains $\sim$ 9x. The results establish a transparent, reproducible baseline and identify feedstock cost, not pyrolysis chemistry, as the binding constraint on carbon-negative economics at this scale.

Keywords: *biochar; slow pyrolysis; wood pellets; mass balance; carbon dioxide removal; wood vinegar; EU ETS; carbon credits*

1. Introduction

Biochar - the carbon-rich solid produced when biomass is heated in the absence of, or with limited, oxygen - has attracted sustained interest as a soil amendment, a filtration and adsorption medium, and, increasingly, as one of the few durable carbon dioxide removal (CDR) pathways available at scale today. Biochar already accounts for the large majority of delivered durable CDR credits, and the voluntary market for these credits has grown rapidly, with several million tonnes of CO_2 contracted in recent years [6, 7]. Its appeal rests on a simple physical fact: pyrolysis converts labile plant carbon, which would otherwise return to the atmosphere within years through decay, into a recalcitrant aromatic carbon form that can persist in soils for centuries.

Despite the maturity of the underlying chemistry, the gap between laboratory demonstration and economically viable, carbon-negative production remains poorly characterized for small-scale and artisanal systems. Reported biochar yields from slow pyrolysis of woody biomass span a wide range, typically 20-35 % of feedstock mass, and depend strongly on peak temperature, heating rate, and residence time [1, 2, 4]. Carbon retention and char properties such as bulk density, porosity, and surface

area are similarly sensitive to process conditions [1, 3, 8]. Yet many reports present yields and properties without a closed mass balance, making it difficult to account for the fate of the feedstock carbon or to convert laboratory yields into defensible cost and carbon-credit figures.

This paper takes the opposite approach. Rather than optimizing a process variable, it documents a single, completely accounted batch in full: every input and output stream weighed, the off-gas tested, the char characterized for bulk density, and the result translated into a transparent cost per kilogram of char and per tonne of CO₂-equivalent sequestered. The aim is a reproducible reference point - a snapshot - against which subsequent batches, alternative feedstocks, and scale-up decisions can be compared. A standardized, certified feedstock (ENplus A1 wood pellets) was deliberately chosen so that the feedstock variable is fixed and well specified, isolating the behaviour of the reactor and the economics of the conversion.

Three questions frame the analysis. First, what is the complete mass balance of the batch, and how much of the input is unaccounted for as non-condensable gas and losses? Second, how do the resulting biochar yield and density compare with literature values for slow pyrolysis of wood? Third, what does the batch cost to produce, and how far is that cost from the prevailing price of carbon under the EU Emissions Trading System (EU ETS)?

2. Materials and Methods

2.1 Feedstock

The feedstock was MM Royal wood pellets (ENplus A1 certified, certificate AT 002; produced in Austria from softwood, predominantly fir/spruce), supplied in 15 kg bags. Manufacturer specifications list a moisture content of $\leq 8\%$, ash content $\leq 0.5\%$, net calorific value ≥ 4.9 kWh kg⁻¹, and a bulk density in the range 600-750 kg m⁻³. The external firing fuel was chopped, air-dried pine drawn from the same wood-fuel market as the pellets; it was used solely to heat the reactor and did not enter the pyrolysis tube. Feedstock properties are summarized in Table 1.

Property	Value (manufacturer specification)
Material	Softwood pellets (fir/spruce)
Certification	ENplus A1 (AT 002)
Moisture content	$\leq 8\%$
Ash content	$\leq 0.5\%$
Net calorific value	≥ 4.9 kWh kg ⁻¹
Bulk density	600-750 kg m ⁻³
Packaging	15 kg bags

Table 1. Feedstock specification for the MM Royal ENplus A1 wood pellets used in this batch.

2.2 Reactor and procedure

Pyrolysis was carried out in a small tube-in-tube reactor (Figure 1). Wood pellets were loaded into a sealed inner steel tube, which was placed concentrically inside an outer tube heated externally by a wood fire. With the inner tube sealed, the pellets pyrolyzed under an oxygen-limited atmosphere, the evolved volatiles displacing residual air. Volatile vapours were drawn off through a side port and passed through a condenser; the condensable fraction was collected as wood vinegar (pyroligneous liquid), while the non-condensable gases (pyrogas) were vented past the condenser outlet. The batch was run for 40 min. The pyrolysis endpoint was defined operationally as the cessation of visible wood-vinegar condensation at the condenser, taken to indicate that the bulk of the volatile fraction had been driven off.

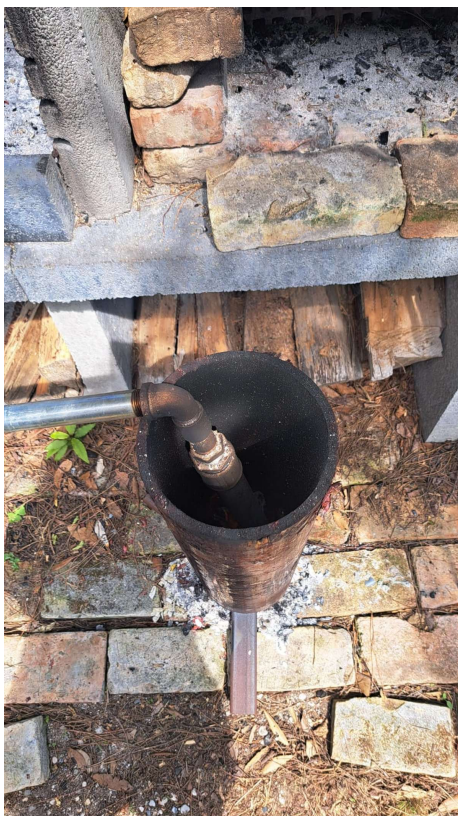


Figure 1. *The tube-in-tube reactor. The sealed inner steel tube holding the pellets sits inside an externally wood-fired outer tube; the angled take-off pipe carries volatiles to the condenser.*

2.3 Measurements

All solid and liquid streams were weighed on a balance: pellets charged (as received), external firing fuel consumed, solid biochar recovered, and condensed wood vinegar. The mass of non-condensable gas plus minor system losses was determined by difference from the input pellet mass. The bulk density of the biochar was determined by measuring the mass of char occupying a known volume in a graduated vessel (Figure 2). The non-condensable off-gas was tested for combustibility at the condenser outlet by attempted ignition.



Figure 2. *Inputs and products. Foreground: as-received softwood pellets. Left vessel: recovered biochar in a graduated beaker (used for bulk-density measurement). Right vessel: condensed wood vinegar.*

2.4 Yield and carbon definitions

Biochar yield is reported on two bases to avoid ambiguity. The **as-received yield** is the mass of char divided by the mass of pellets as charged. The **dry-basis yield** divides by the moisture-free pellet mass, computed using the manufacturer moisture specification of 8 %. Mass closure is expressed as the fraction of input pellet mass recovered in identified streams (char plus wood vinegar) versus the fraction unaccounted for. Per-unit yields are normalized to one kilogram of as-received pellet input.

Carbon retention and CO₂-equivalent sequestration are reported as estimates, not measurements, because no ultimate (CHN) analysis of the char or feedstock was performed in this batch. Two clearly delimited assumptions are used. The carbon-retention estimate assumes a feedstock carbon content of ~50 % of dry mass and a char carbon content typical of wood char (~75-80 %), as commonly reported in the literature [1, 3]. The CO₂-equivalent figure is reported on a deliberately conservative basis, corresponding to a lower assumed char carbon content (~56 %); it is therefore intended as a floor rather than a central estimate. Both figures should be treated as provisional pending elemental analysis (Section 4.4).

2.5 Cost basis

Costs are reported on a raw-material basis. Pellets were purchased at EUR 5.60 per 15 kg bag including 22 % value-added tax (IVA), equivalent to EUR 0.37 per kg as paid (EUR 0.31 per kg ex-IVA). The external firing fuel was priced at the same per-kilogram rate, since it derives from the same wood-fuel market. The wood-vinegar co-product was assigned zero value. Labour, equipment depreciation, and energy beyond the firing fuel are excluded; the figures therefore represent a lower bound on true production cost. For the carbon-credit benchmark, the EU ETS allowance price was taken as approximately EUR 74-75 per tonne CO₂, its level in May 2026 [5].

3. Results

3.1 Mass balance

The complete mass balance for the batch is given in Table 2. Of 349.5 g of pellets charged, 212.1 g were recovered in identified streams - 97.3 g of biochar and 114.8 g of wood vinegar - leaving 137.4 g, or 39.3 % of the input mass, unaccounted for. This balance is closed against the pellet input only; the 1,549 g of external firing fuel is reported separately because it heats the reactor and does not enter the pyrolysis tube. The unaccounted fraction is attributed primarily to non-condensable gas escaping past the condenser, together with minor vapour losses and char fines not recovered.

Stream	Mass
Pellets in (as-received)	349.5 g
External firing fuel consumed (chopped dry pine)	1,549 g
Biochar out	97.3 g
Wood vinegar condensed	114.8 g
Non-condensable gas + losses (by difference)	137.4 g

Table 2. Batch mass balance. Closure is computed on the pellet input; identified outputs (char + wood vinegar) total 212.1 g, leaving 137.4 g (39.3 %) unaccounted. External firing fuel is listed for completeness but is not part of the pyrolysis-tube balance.

3.2 Yield and char properties

The biochar yield was 27.8 % on an as-received basis (97.3 g from 349.5 g) and 30.3 % on a dry basis after correcting for 8 % feedstock moisture. The dry-basis figure sits in the upper half of the 20-35 % range characteristic of slow pyrolysis of woody biomass [1, 2, 4]. The char bulk density was 324 kg m⁻³, approximately half the 600-750 kg m⁻³ of the parent pellets. Combined with the 72 % reduction in mass, this density loss reflects the development of internal pore structure - the porosity and surface area that underpin biochar's value as a soil amendment, adsorbent, and carbon scaffold [3, 8]. Per-unit yields normalized to one kilogram of as-received pellet input are given in Table 3.

Output (per kg pellets in)	Yield
Biochar	278 g
Biochar bulk volume	858 mL
Wood vinegar	328 g
Non-condensable gas + losses	393 g
CO ₂ -equivalent sequestered (conservative)	~570 g

Table 3. Per-unit yields normalized to one kilogram of as-received pellet input. The CO₂-equivalent figure is a conservative estimate (see Section 2.4).

3.3 Off-gas (pyrogas) quality

The non-condensable gas leaving the condenser was tested for combustibility and did not sustain ignition. This is consistent with the well-documented low calorific value of wood-derived producer gas, which is diluted by carbon dioxide and typically requires preheating, enrichment, or recirculation to be useful as a fuel. In the present configuration the pyrogas represents an energy stream that is neither captured nor combusted, and instead appears in the mass balance as part of the unaccounted fraction.

3.4 Carbon retention

Under the assumptions defined in Section 2.4, the estimated carbon retention from feedstock to solid char is approximately 48 %, with the balance leaving as condensate and off-gas. The conservative CO₂-equivalent sequestration corresponds to roughly 200 g CO₂-eq per batch, or ~570 g per kilogram of pellets charged (Table 3). These two figures rest on different assumed char carbon contents and are reconciled in Section 4.4; both are presented as provisional estimates rather than measured values.

3.5 Economics

On a raw-material basis, the batch consumed EUR 0.13 of pellets and EUR 0.58 of external firing fuel, a total of EUR 0.71 (Table 4). Against 97.3 g of char recovered, this is a production cost of approximately EUR 7.29 per kg of biochar. Expressed per unit of carbon removed, and using the conservative ~200 g CO₂-eq per batch, the implied cost is approximately EUR 3,540 per tonne CO₂-equivalent.

Cost basis (incl. IVA)	Value
Pellets per batch (349.5 g)	EUR 0.13
External firing fuel per batch (1,549 g)	EUR 0.58
Total raw material per batch	EUR 0.71
Per kg of biochar produced	EUR 7.29
Per tonne CO₂-eq sequestered (~200 g/batch)	~EUR 3,540

Table 4. Raw-material cost analysis. Labour, equipment, and energy beyond the firing fuel are excluded; figures are a lower bound on true production cost.

4. Discussion

4.1 Yield and char quality in context

The dry-basis yield of 30.3 % is unremarkable in the best sense: it falls squarely within, and toward the upper half of, the 20-35 % band reported for slow pyrolysis of woody biomass, and is close to specific literature values such as ~29 % from forest harvest residues at 450 C and ~31 % from pine wood at 450 C [2, 4]. The certified, low-ash, low-moisture pellet feedstock behaved predictably and produced a dense, structurally coherent char. The measured bulk density of 324 kg m⁻³ is consistent with pelletized and pellet-derived biochars reported in the range of roughly 210-380 kg m⁻³ depending on pyrolysis temperature [8]. The halving of density relative to the feedstock, alongside a 72 % mass reduction, is the macroscopic signature of pore development and is the property most directly relevant to downstream use as a soil amendment or adsorbent.

4.2 The unaccounted fraction

Closing the balance to within identified streams left 39.3 % of the input unaccounted. This is not anomalous for a slow-pyrolysis batch: the non-condensable gas fraction of wood pyrolysis is commonly 20-35 % of feedstock mass, and additional small losses arise from incomplete condensate recovery and char fines. Nonetheless, the size of the gap is the principal limitation on the precision of the carbon accounting, because the carbon embodied in that fraction is estimated rather than measured. Quantifying the gas stream directly - by volume and composition - would convert the largest source of uncertainty in this snapshot into a measured quantity.

4.3 Pyrogas cannot be flared directly

The finding that the off-gas does not sustain ignition has a practical consequence for reactor design. Recovering the energy of the pyrogas cannot be achieved simply by flaring it at the condenser outlet. It requires engineering the gas back into the process - preheating and recirculating it through the fire, where it can contribute to the heat of pyrolysis even at low calorific value. This is the pathway toward autothermal operation, in which the process volatiles supply the heat and the external firing fuel is reduced or eliminated. The economic significance of that transition is quantified below.

4.4 Reconciling the two carbon estimates

The two carbon figures reported in Section 3.4 rest on different assumptions and should not be conflated. A carbon retention of ~48 % implies a char carbon content of roughly 79 % of char mass (taking feedstock carbon at ~50 % of dry mass), which is typical for wood char produced at moderate-to-high pyrolysis temperatures. The conservative CO₂-equivalent figure of ~200 g per batch instead implies a char carbon content of only ~56 %, a deliberately low value chosen so as not to overstate sequestration. The two are therefore endpoints of a plausible range rather than a contradiction: actual carbon storage in this batch most likely lies between them. The single most valuable measurement to add in future work is an ultimate (CHN) analysis of the char, ideally with the molar H/C_{org} ratio, which both pins down carbon content and serves as the standard durability indicator ($H/C_{org} < 0.7$) required by biochar carbon-credit methodologies [7].

4.5 Carbon-credit economics and the binding constraint

The economic picture is stark and is the central result of this snapshot. At an implied ~EUR 3,540 per tonne CO₂-equivalent, this batch is roughly 45-47x more expensive than the May 2026 EU ETS allowance price of ~EUR 74-75 per tonne [5], and still well above the EUR 125-165 per tonne range at which premium biochar carbon-removal credits have recently traded in the voluntary market [6, 7]. The dominant cost is not the feedstock that becomes char but the external fuel used to heat the reactor: firing fuel accounts for EUR 0.58 of the EUR 0.71 raw-material cost, more than four-fifths of the total. Eliminating it through autothermal operation would cut the implied carbon cost to roughly EUR 650 per tonne - still about 9x the ETS benchmark, but an order of magnitude closer.

The remaining gap after autothermal operation is a scale-and-supply problem rather than a chemistry problem. The pyrolysis itself works: yields, density, and char quality are all in line with the literature. What does not work at this scale is paying market price for high-quality certified pellets as a CDR feedstock.

Closing the residual gap requires feedstock that is cheap or, better, waste-derived - residues that carry a near-zero or negative acquisition cost - together with the throughput needed to amortize equipment and labour, neither of which a single artisanal batch can provide. This reframes the economic challenge away from improving the conversion and toward securing low-cost biomass supply and scale.

4.6 Limitations

This is a single batch and the figures should be read as a snapshot, not a characterization with statistical confidence. The principal limitations are: (i) the 39.3 % unaccounted mass fraction, whose carbon content is estimated rather than measured; (ii) the absence of elemental (CHN) analysis, surface-area (BET), and ash measurements on the char, which leaves carbon retention, durability, and quality estimated from literature analogues; (iii) the lack of direct temperature logging, so peak temperature and heating profile are inferred from the operational endpoint rather than recorded; and (iv) a cost basis restricted to raw materials, excluding labour, equipment, and energy, which understates true production cost. None of these undermines the central economic conclusion, which is robust to the carbon-accounting uncertainty: even on the most favourable assumptions, the cost gap to the carbon-price benchmark is an order of magnitude or more.

5. Conclusions

A single, fully weighed batch of biochar from certified softwood pellets produced a dry-basis yield of 30.3 % and a char bulk density of 324 kg m⁻³, both consistent with literature values for slow pyrolysis of wood, alongside a 72 % mass reduction indicative of well-developed porosity. The mass balance closed to identified streams within 60.7 % of input, with the remaining 39.3 % attributed to non-combustible pyrogas and minor losses. Three conclusions follow. First, the conversion chemistry is sound and reproducible: a certified pellet feedstock yields a dense, well-structured char with predictable mass balance. Second, the pyrogas does not flare directly and its energy can only be recovered by recirculation, which is also the route to autothermal operation. Third, and most importantly, the economics are dominated by the cost of external firing fuel, and even after removing it the implied carbon-removal cost remains roughly nine times the prevailing carbon price. The binding constraint on carbon-negative biochar at this scale is therefore feedstock cost and throughput, not pyrolysis performance. The clearest priorities for future work are direct quantification of the gas stream, elemental analysis of the char, and a shift to waste-derived feedstock at greater scale.

Data Availability and Notes

All primary measurements supporting this study are reported in Tables 2-4. The biochar, wood vinegar, and feedstock samples are shown in Figures 1 and 2. The author declares no competing financial interest. Carbon-retention and CO₂-equivalent figures are estimates pending elemental analysis, as detailed in Sections 2.4 and 4.4.

References

1. Domingues, R. R., Trugilho, P. F., Silva, C. A., et al. *Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits*. *PLoS ONE* (2017). <https://doi.org/10.1371/journal.pone.0176884>
2. Stepacheva, A., Lugovoy, Y., Molchanov, V., et al. *Biochar from wood waste: textural and structural properties depending on production method*. *Chemical Engineering Transactions* 114, 121-126 (2024). <https://doi.org/10.3303/CET24114021>
3. Cradle-to-gate life cycle analysis of slow pyrolysis biochar from forest harvest residues in Ontario, Canada. *Biochar* (2024). <https://link.springer.com/article/10.1007/s42773-024-00352-z>
4. Effect of pyrolysis temperature on the physical and chemical characteristics of pine wood biochar. *Bioresource Technology Reports* (2024). <https://www.sciencedirect.com/science/article/pii/S2949750724000981>
5. EU Carbon Permits - price and historical data; EU carbon allowance prices, May 2026 (~EUR 74-75/t CO₂). Trading Economics / IndexBox. <https://tradingeconomics.com/commodity/carbon>
6. Biochar Carbon Removal Market Snapshot 2025: prices, volume and trends. CDR.fyi. <https://www.cdr.fyi/blog/biochar-carbon-removal-market-snapshot-2025>
7. Are biochar carbon credits reliable? What to look for. Sylvera (incl. H/Corg durability criterion). <https://www.sylvera.com/blog/biochar-carbon-credits>
8. Dumroese, R. K., et al. Pelleted biochar: chemical and physical properties. USDA Forest Service. https://www.fs.usda.gov/rm/pubs_other/rmrs_2011_dumroese_r002.pdf