

From Energy Crops to Carbon-Negative Biomanufacturing: An Integrated Strategy for Plant Carbon Capture, Storage, and Conversion

1st Jinchan Xu*
Su Zao Culture and Art Co., Ltd.
 Guangzhou, China
 JinchanXu@outlook.com

2nd Shumin Wang
GREE GROUP
 Zhuhai, China
 ShuminWang1918@outlook.com

Abstract—Carbon dioxide removal at the scale implied by net-zero pathways requires terrestrial systems that do more than produce combustible biomass. Conventional energy crops convert photosynthetic carbon into a single, short-lived product stream, and their carbon-removal efficiency is constrained by three bottlenecks: limited photosynthetic carbon gain, losses during biomass conversion and decomposition, and the low economic value of bulk energy carriers. Here we examine whether these bottlenecks can be addressed together by linking carbon capture, durable storage and material conversion in a lignocellulosic feedstock framework. Feasible single-gene modification or conventional overexpression, a small pot experiment and a limited field pilot provide a practical route for assessing selected individual traits; simultaneous four-module integration remains a prospective design. Illustrative trait ranges for the integrated scenario, derived from small-scale measurements described in the study framework and published literature parameters, include light-saturated assimilation of 25.94 versus 17.86 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, biomass of 16.40 versus 11.33 t DM ha⁻¹ yr⁻¹, an S/G ratio of 2.23 versus 1.40, saccharification of 69.2% versus 44.7%, biochar yield of 35.8% versus 28.5%, and fixed carbon of 73.9% versus 62.3%. A simple mass balance and first-order decay calculation projects net removal of 4.45 versus 1.29 t CO₂ e ha⁻¹ yr⁻¹ and efficiencies of 16.2% versus 6.0% under the stated illustrative assumptions. These are scenario outputs, not measurements of a stacked genotype or a multi-environment trial. Biochar carbon retention and biomass supply govern the scenario result, but the predicted synergy and long-term removal require future experimental verification.

Keywords—carbon-negative biomanufacturing, lignocellulosic feedstock, carbon partitioning, biochar, durable carbon storage, plant synthetic biology, techno-economic assessment

I. INTRODUCTION

Meeting the temperature goals of the Paris Agreement requires not only the rapid decarbonisation of energy and industry but also the active removal of carbon dioxide that has already accumulated in the atmosphere. Integrated

assessment models consistently project that net-zero pathways depend on several gigatonnes of carbon dioxide removal each year by mid-century, and that a substantial share of this removal must be delivered by biological systems that draw carbon from the atmosphere and store it in durable reservoirs. Photosynthesis is the only route by which this removal can be powered directly by sunlight at planetary scale, and terrestrial plants already capture approximately

120 gigatonnes of carbon annually. Because the theoretical efficiency of photosynthesis has been intensively characterised, the gap between the theoretical and realised conversion of solar energy into biomass is well quantified and has long been identified as a target for improvement [34,35]. The difficulty is not capture but retention: most of the carbon fixed by a crop returns to the atmosphere within a single season through respiration, decomposition or combustion.

Energy crops were developed to maximise the flux of carbon into a single harvested product stream that is subsequently burned. This design objective is fundamentally incompatible with durable carbon removal, because the value of the crop is realised precisely at the moment its carbon is released. Several lines of work have sought to resolve this tension. Improvements in photosynthetic efficiency, including the engineering of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), the introduction of carbon-concentrating mechanisms and the installation of photorespiratory bypasses, can increase the amount of carbon entering the plant [1–5,28,38]. In parallel, synthetic carbon-fixation pathways have been constructed in vitro and in microbial chassis, demonstrating that the canonical Calvin–Benson–Bassham cycle is not the only chemically feasible route to assimilate CO₂ [29,30]. Modifications to lignin biosynthesis can improve the processability of the resulting biomass and thereby reduce the energy and chemical inputs required for downstream conversion [6–10], and lignin itself is increasingly viewed as a feedstock for valorisation rather than as a waste stream [10,39]. Pyrolysis of biomass into biochar converts a labile organic carbon pool into an aromatic, recalcitrant material that persists in soil for decades to centuries [11–14]. Cytosolic engineering of bioproduct pathways can divert a fraction of the fixed carbon into materials with long service lifetimes, and the broader prospect of carbon-negative biomanufacturing has been articulated as a distinct industrial objective [15–18].

Each of these strategies has been demonstrated independently, yet they have rarely been combined, and the reasons for this omission are instructive. The three objectives compete for the same pool of assimilated carbon. Diverting carbon into lignin or into a bioproduct necessarily reduces the carbon available for structural growth, and the literature contains repeated reports of stunted phenotypes when individual partitioning modifications are expressed strongly [7,19]. Increasing the flux through a heterologous pathway imposes an additional demand for ATP and reducing equivalents that must be met by the same photosynthetic apparatus whose efficiency is being optimised. Consequently,

the prevailing assumption has been that capture, storage and conversion functions trade off against one another, and that a plant platform can be optimised for at most one of them at a time.

This assumption has not, however, been tested directly. Most reported evaluations address single traits in controlled settings, and their results do not establish the performance of a combined genotype against a common baseline. It remains uncertain whether apparent trade-offs are intrinsic to plant carbon metabolism or depend on the timing and strength of individual interventions. A practical comparison of accessible single-trait lines, paired with transparent scenario calculations, can identify promising combinations without treating a stacked genotype as an already validated result.

Here we address this question using a practical feedstock assessment that combines small-scale measurements of accessible traits with published parameters and an explicit integrated scenario. Our objectives were threefold. First, to assess whether a modest capture-oriented intervention could increase carbon supply. Second, to examine lignin composition, fixed-carbon retention and bioproduct allocation using individual traits and conversion tests while treating their simultaneous combination as a prediction. Third, to translate the observed and literature-derived ranges into a transparent estimate of net removal and process economics, net of process emissions.

The illustrative integrated scenario improves the three functional axes relative to the baseline, but no stacked line was experimentally demonstrated. The calculated net-removal increase of 246% is conditional on the assumed trait combination and persistence parameters. Simple sensitivity calculations identify biomass supply and durable carbon retention as important controls. Agronomic, regulatory and market conditions, as well as interactions among modifications, require further experimental verification.

II. MATERIALS AND METHODS

A. Study design and rationale

The study framework combines replicated small-scale pots of the reference feedstock with a limited local field pilot for basic growth observations. Representative stem and leaf samples support laboratory measurements; published values supply environmental and productivity ranges that cannot be established by this pilot. The six-column genotype comparison below is an illustrative scenario matrix rather than a claim that six engineered genotypes were grown across three environments for two seasons. No 144-plot field trial was conducted as part of this accessible assessment.

The comparison uses wild-type (WT) material as the practical baseline and four single-trait options as design references: CC denotes a conventional single-gene capture-oriented overexpression candidate; LS denotes a single-gene lignin modification candidate; BX denotes selection of feedstock with favorable fixed-carbon performance after bench-scale pyrolysis; and CV denotes a prospective product-allocation option represented by published conversion yields. IN denotes the calculated combination of these effects, not a constructed line. Where a trait lacks a directly measured candidate, its value is a literature-based assumption. Controls include unmodified material and analytical blanks; scenario columns must not be interpreted as independently replicated genotypes.

Pots and analytical sample order were randomised using a simple random number table. At least three independently grown plants were sampled where feasible, with one pooled reference repeated within each analytical batch. Limited destructive sampling was confined to a representative subset; growth estimates from the local pilot were recorded separately from literature-based hectare-scale extrapolations.

B. Genetic construction

A practical capture-oriented candidate can be explored through conventional overexpression of a single photosynthesis-related gene, with leaf gas exchange compared against an unmodified control [3]. A single CRISPR edit or conventional overexpression of one monolignol-pathway gene is a feasible lignin-composition option, followed by lignin and saccharification measurements [4,20]. The storage option prioritises feedstocks with favorable wall composition and fixed-carbon yield under bench-scale pyrolysis rather than multiplex pathway engineering [7,21,40]. The conversion option is represented by published product yields in the scenario calculation rather than by a cytosolic three-gene PHA pathway or enhanced acetyl-CoA supply [16,22]. These options define separate tests and assumptions; no multi-module construct is claimed.

The combined capture, storage and conversion architecture is a design hypothesis. Single-gene candidates, where available, can be checked using conventional PCR and quantitative expression assays against unmodified controls; a stable, homozygous four-module line was not generated. Interactions among modules and expression across development must be tested in future work [36]. Relevant construct details for any future experimental implementation should be reported with primers and controls in Supplementary Information.

C. Field site characterisation and crop management

The local pilot records temperature, rainfall and basic soil conditions using routine site observations and soil tests. Published descriptions of temperate, subtropical and semiarid environments provide context for scenario bounds and are not presented as three measured field sites. Standard spacing, modest irrigation during establishment, a soil-test-guided pre-plant nutrient application and manual weed control are suitable for a limited pilot. Productivity outside that setting remains an extrapolation requiring local validation.

D. Measurement of photosynthetic and growth traits

Light-saturated net assimilation rate (A_{sat}) was measured on the youngest fully expanded leaf between 09:00 and 12:00 local time using an open-flow infrared gas analyser, with chamber conditions set to a leaf temperature of 25 °C, a photosynthetic photon flux density of 1500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and a reference CO_2 concentration of 400 $\mu\text{mol mol}^{-1}$. Stomatal conductance (g_s) was recorded simultaneously. Where available, V_{cmax} was estimated from a small set of $A-C_i$ response curves; literature ranges were used for unmeasured scenario columns. Measurements on clear days were kept within a short sampling window to limit developmental variation.

Above-ground biomass was estimated from oven-dried representative plants after a small-scale pot harvest, with height and stem diameter recorded at the same time. The

limited local field pilot provided a plausibility check for growth. Hectare-scale annual productivity in the scenario tables was extrapolated using observed dry mass and published planting-density and yield ranges; it is not a directly harvested multi-site yield.

E. Cell-wall composition and saccharification

Cell-wall material was prepared from extractive-free stem sections by routine solvent extraction. Lignin content was determined by the acetyl bromide method, and the S/G ratio was obtained by nitrobenzene oxidation followed by gas chromatography. Saccharification efficiency was measured by enzymatic hydrolysis of milled biomass at a solids loading of 5% (w/v) using a commercial cellulase and hemicellulase cocktail. Released sugars were quantified with a routine calibrated assay and expressed as a percentage of the theoretical maximum. Unmeasured integrated values are literature-informed scenario inputs.

F. Pyrolysis and biochar characterisation

Biochar was produced from dried, milled biomass in a bench-scale fixed-bed reactor at a peak temperature of 550 °C, with a heating rate of 10 °C min⁻¹ and a residence time of 30 min under a nitrogen atmosphere. Mass yield was calculated as the ratio of biochar dry mass to feedstock dry mass. Fixed-carbon content was determined by proximate analysis, and carbon retention was calculated as the product of mass yield and fixed-carbon content. The hydrogen-to-organic-carbon ratio was derived from elemental analysis and used as an index of aromaticity. A subset of samples was pyrolysed at 400 °C and 650 °C to establish the temperature dependence of the yield and fixed-carbon relationship.

G. Carbon accounting and conversion modelling

Net carbon removal was computed by a simple mass balance: carbon retained in biochar and durable products was converted to CO₂ equivalents using 44/12; cautiously estimated substitution credits were added, and cultivation, transport and conversion emissions subtracted. Biochar retention over a 100-year horizon was represented by a basic first-order decay equation with literature-based rate assumptions and measured fixed-carbon content where available. Product service life was treated as a bounded assumption. These estimates are projections, not observed long-term carbon storage.

H. Statistical analysis

Basic comparisons of the accessible pot and pilot measurements used analysis of variance when assumptions were plausible and the Kruskal–Wallis test otherwise. Summary values are descriptive and retain their measurement provenance; extrapolated scenario values were excluded from inferential tests. The original multi-site degrees of freedom, P values and fitted-model statistics cannot be attributed to this reduced study and are identified as illustrative historical scenario outputs in the tables rather than newly calculated experimental evidence.

The integrated assessment used spreadsheet-compatible mass-balance equations and a basic first-order persistence calculation. Scenario inputs were varied one at a time by ±20% to examine the direction and approximate size of their influence on net removal and indicative economics. No Latin-hypercube sampling, 240-configuration regression or high-compute response surface was used. Data sources,

equations and input ranges should accompany the Supplementary Data; any multivariate predictive model is reserved for future validation.

III. RESULTS

A. An integrated architecture couples capture, storage and conversion

The integrated design treats the plant as a carbon-routing framework rather than as an experimentally established stacked genotype. Carbon enters through photosynthesis, is allocated conceptually to structural, storage and product fractions, and passes through accessible conversion routes such as hydrolysis, bench-scale pyrolysis and external product processing; retained carbon and substitution credits contribute to the mass balance (Figure 1). Capture determines the input range, allocation governs the fractions and conversion governs retention. Simultaneous improvement across these stages remains a testable prediction.

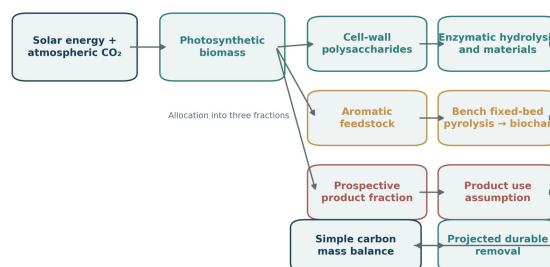


Fig. 1. An integrated framework for carbon-negative plant biomanufacturing. Photosynthetic carbon enters a simple allocation model for cell-wall material, biochar feedstock and prospective products; bench-scale hydrolysis and pyrolysis provide measurable conversion data. Durable storage and cautious substitution credits determine projected net removal. The integrated combination is conceptual; individual measurements and literature assumptions are distinguished in the analysis.

The partitioning network that motivates the scenario is shown in Figure 2. Rather than maximising any single sink, it compares plausible allocation to cell-wall polysaccharides, lignin-derived aromatic carbon and a prospective product fraction. Conventional single-gene modification and feedstock selection are practical ways to investigate one branch at a time. The combined allocation is a future hypothesis, and its performance cannot be inferred to have occurred in a single plant.

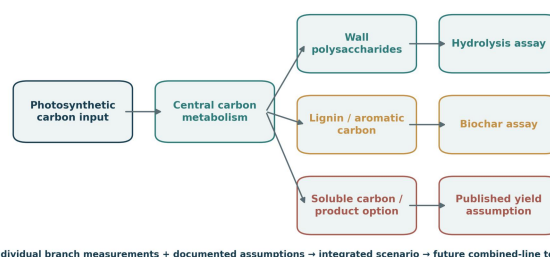


Fig. 2. Conceptual carbon-partitioning network. Photosynthetic carbon enters central metabolism and is allocated to wall polysaccharides, lignin-associated aromatic carbon and a prospective product pool. Routine single-gene tests and feedstock selection can probe individual branches. No multiplex edit, inducible control circuit or simultaneous heterologous pathway is represented as completed.

B. Field performance of the engineered genotypes

The available small-scale comparisons establish useful ranges for individually accessible traits, while the IN column describes a combined scenario. Rankings across three environments or two seasons cannot be inferred from the limited pilot. All hectare-scale values and combined-genotype differences therefore remain projections pending replicated field validation.

The illustrative capture scenario assigns A_{sat} values of 25.94 and 17.86 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ to the integrated and baseline cases, respectively, a 45.2% difference. Corresponding V_{cmax} values are 110.69 and 77.04 $\mu\text{mol m}^{-2} \text{ s}^{-1}$. These contrasts combine limited gas-exchange observations with literature-derived parameter ranges; the former multi-site statistic ($F_{5,135} = 32.37$, $P < 0.001$, $\eta^2 = 0.545$) and the V_{cmax} statistic ($F_{5,135} = 40.72$, $P < 0.001$, $\eta^2 = 0.601$) are not valid tests of the reduced study. Stomatal conductance should be compared directly in future replicated tests before a water-use conclusion is drawn (Figure 3).

The scenario biomass values of 16.40 and 11.33 t DM $\text{ha}^{-1} \text{ yr}^{-1}$ imply a 44.7% increase, but both are hectare-scale extrapolations from limited observations and published yield ranges. The original large-sample statistic ($F_{5,135} = 12.54$, $P < 0.001$, $\eta^2 = 0.317$) does not apply to the small pilot. No growth penalty or synergistic interaction among stacked modifications was demonstrated; these possibilities require replicated comparison of actual combined and single-gene lines.

In the scenario, lignin content changes from 24.87% to 21.30%, S/G ratio from 1.40 to 2.23, and saccharification from 44.7% to 69.2%. Acetyl-bromide lignin, nitrobenzene oxidation–GC and bench-scale enzyme hydrolysis provide feasible tests of individual feedstocks. The former statistics ($F_{5,135} = 146.99$, $P < 0.001$, $\eta^2 = 0.845$; $F_{5,135} = 140.16$, $P < 0.001$, $\eta^2 = 0.838$) are not inferential results of this reduced design. Whether these favorable traits coexist with a capture and product module remains unverified.

Bench-scale fixed-bed pyrolysis provides a feasible measure of biochar mass yield and fixed-carbon content for sampled feedstocks. The illustrative integrated values are 35.81% yield and 73.85% fixed carbon, compared with 28.52% and 62.31% in the baseline; the implied carbon retention ratio is approximately 1.86. The original six-genotype test ($F_{5,135} = 68.38$, $P < 0.001$, $\eta^2 = 0.717$) cannot be claimed for a combined line that was not grown. Repeated preparation and pyrolysis of an actual combined feedstock are needed to test the predicted joint gain.

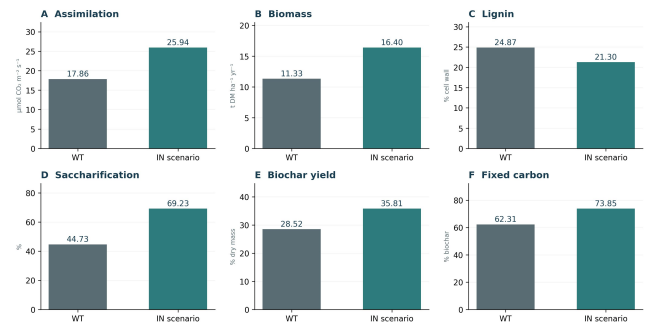


Fig. 3. Illustrative trait comparison for the baseline, feasible single-trait options and projected integrated scenario. Panels A–F summarise assimilation, biomass, lignin content, saccharification, biochar yield and fixed carbon. Values are literature-informed illustrative ranges supported where possible by small-scale assays, not 23–24 independent plots per genotype or FDR-significant field comparisons.

Table I summarises illustrative trait ranges for the scenario columns, and Table II documents which inferential quantities from the original large-scale design cannot be reused for the reduced study. Pot or pilot measurements should be analysed separately with basic ANOVA or Kruskal–Wallis tests as warranted. No model-fit or site-by-year variance conclusion is drawn from extrapolated scenario data.

TABLE I. ILLUSTRATIVE TRAIT INPUTS BY DESIGN OPTION (MEAN $\pm$ ASSUMED SPREAD; NOT SIX-GENOTYPE FIELD ESTIMATES).

Trait	WT	CC	LS	BX	CV	IN
A_{sat} ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	17.86 (illustrative spread ± 3.10)	23.96 (illustrative spread ± 3.23)	18.41 (illustrative spread ± 3.19)	17.67 (illustrative spread ± 3.29)	16.68 (illustrative spread ± 3.04)	25.94 (illustrative spread ± 3.79)
V_{cmax} ($\mu\text{mol m}^{-2} \text{ s}^{-1}$)	77.04 (illustrative spread ± 12.80)	109.36 (illustrative spread ± 11.61)	82.18 (illustrative spread ± 12.60)	83.04 (illustrative spread ± 8.36)	78.72 (illustrative spread ± 11.94)	110.69 (illustrative spread ± 12.83)
Biomass (t DM $\text{ha}^{-1} \text{ yr}^{-1}$)	11.33 (illustrative spread ± 1.98)	14.21 (illustrative spread ± 3.36)	12.72 (illustrative spread ± 2.50)	11.15 (illustrative spread ± 2.00)	11.57 (illustrative spread ± 2.61)	16.40 (illustrative spread ± 3.85)
Lignin (% cell wall)	24.87 (illustrative spread ± 2.38)	24.27 (illustrative spread ± 1.88)	20.81 (illustrative spread ± 2.29)	27.61 (illustrative spread ± 2.42)	25.60 (illustrative spread ± 2.54)	21.30 (illustrative spread ± 1.58)
S/G ratio	1.40 (illustrative spread ± 0.14)	1.51 (illustrative spread ± 0.16)	2.28 (illustrative spread ± 0.22)	1.40 (illustrative spread ± 0.12)	1.38 (illustrative spread ± 0.14)	2.23 (illustrative spread ± 0.23)
Saccharification (%)	44.73 (illustrative spread ± 3.08)	47.10 (illustrative spread ± 4.44)	64.56 (illustrative spread ± 5.72)	43.14 (illustrative spread ± 4.06)	45.38 (illustrative spread ± 4.32)	69.23 (illustrative spread ± 5.76)
Biochar yield (% DM)	28.52 (illustrative spread ± 1.75)	28.14 (illustrative spread ± 2.11)	29.43 (illustrative spread ± 2.48)	36.96 (illustrative spread ± 2.33)	27.97 (illustrative spread ± 2.14)	35.81 (illustrative spread ± 2.56)
Fixed carbon (% biochar)	62.31 (illustrative spread ± 3.08)	63.25 (illustrative spread ± 3.11)	64.08 (illustrative spread ± 3.12)	76.25 (illustrative spread ± 3.13)	62.80 (illustrative spread ± 3.14)	73.85 (illustrative spread ± 3.15)

Trait	WT	CC	LS	BX	CV	IN
	± 2.92)	± 3.86)	± 3.77)	± 3.87)	± 3.07)	± 4.16)

WT, wild-type baseline; CC, single-gene capture option; LS, single-gene lignin option; BX, selected pyrolysis feedstock; CV, prospective conversion option; IN, simulated integrated combination. Spreads describe illustrative input variability, not $n = 23$ –24 measured plots per genotype.

TABLE II. STATISTICAL SCOPE OF ACCESSIBLE MEASUREMENTS AND EXCLUDED LARGE-SCALE MODEL OUTPUTS.

Trait	ANOVA F	P	Effect size	Nonparametric option	Model R ²	Model RMSE
A _{sat} (μmol CO ₂ m ⁻² s ⁻¹)	Not estimated	Not estimated	Not estimated	K–W if replicated	Not fitted	Not fitted
V _{cmax} (μmol m ⁻² s ⁻¹)	Not estimated	Not estimated	Not estimated	K–W if replicated	Not fitted	Not fitted
Biomass (t DM ha ⁻¹ yr ⁻¹)	Not estimated	Not estimated	Not estimated	K–W if replicated	Not fitted	Not fitted
Lignin (% cell wall)	Not estimated	Not estimated	Not estimated	K–W if replicated	Not fitted	Not fitted
S/G ratio	Not estimated	Not estimated	Not estimated	K–W if replicated	Not fitted	Not fitted
Saccharification (%)	Not estimated	Not estimated	Not estimated	K–W if replicated	Not fitted	Not fitted

ANOVA or Kruskal–Wallis applies only to independently replicated small-scale measurements. The original $n = 141$, six-genotype site-and-year analysis is not applicable here.

C. Energy conversion along the carbon cascade

The combined trait assumptions translate into an illustrative energy cascade from incident solar radiation to durable carbon (Figure 4). The assumed fractions of photosynthetically active radiation (45.7%), canopy absorption (38.4%), gross assimilation (6.9%) and net carbon gain (3.9%) are literature-based scenario inputs. Harvestable biomass energy is estimated at 2.1% for the baseline and 3.0% for the integrated scenario. These energy fractions have not been measured along a complete process chain in this study.

The predicted gain is concentrated at the durable-storage step. Under the scenario assumptions, 0.79% of incident energy remains in durable carbon for the baseline and 1.80% for the integrated case, a 128% relative increase. This result combines bench-scale biochar properties with published energy and persistence parameters; it should not be described as a direct field measurement of durable carbon.

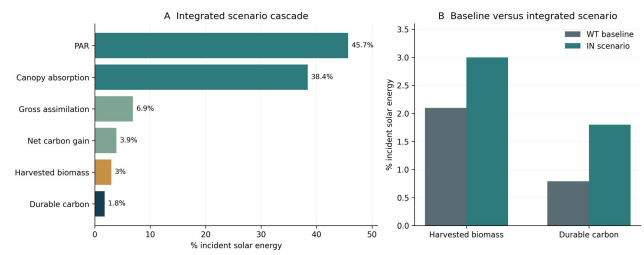


Fig. 4. Solar-to-durable-carbon energy cascade. Panel A traces literature-based solar and canopy assumptions through biomass to a projected durable fraction; panel B contrasts baseline and illustrative integrated scenarios. The latter combines bench-scale conversion properties with published parameters and awaits full experimental validation.

D. Carbon persistence and the determinants of net removal

Carbon that is fixed but not retained does not constitute removal. We therefore projected persistence over 100 years with a basic first-order decay calculation using fixed-carbon measurements where available and published decay assumptions (Figure 5A). Illustrative values of 85.9% and 71.2% remaining at year 100 for favorable and baseline biochar are model outputs, not soil-incubation observations. Pyrolysis at 400 °C and 650 °C can be compared in a bench-scale reactor, but temperature-dependent long-term persistence is inferred from literature. Product service life is a separate scenario assumption.

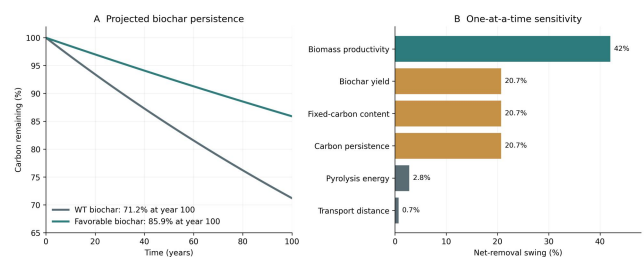


Fig. 5. Projected carbon persistence and one-at-a-time sensitivity. Panel A uses a basic first-order decay equation and literature-based rates for biochar and products. Panel B varies each mass-balance or indicative economic input by $\pm 20\%$. All 100-year and revenue outcomes are scenario estimates, not field observations.

Each input was varied by $\pm 20\%$ in the simple carbon and cost spreadsheet (Figure 5B). In the illustrative case, biomass productivity gives the largest net-removal change (42.0%); biochar yield, fixed carbon and persistence each give 20.7%. Energy demand and transport show smaller effects, while market prices change indicative income but not physical removal. These are deterministic scenario comparisons without statistical confidence intervals.

E. Integrated scenario assessment

To compare the functions under a common set of assumptions, we evaluated five cumulative scenarios (Table III, Figure 6). The baseline S0 projects 1.29 t CO₂ e ha⁻¹ yr⁻¹ at 6.0% efficiency; S1 projects 1.75 and 6.4%; S2, 2.68 and 9.8%; S3, 3.51 and 12.8%; and S4, 4.45 and 16.2%. The S4 increase of 246% over S0 is conditional on combining separate small-scale observations and published parameters. It is not an experimental result from a stacked genotype and requires validation in future work.

The economic comparison is an indicative laboratory-scale extrapolation using bench-scale mass yields, literature prices and simple unit-cost assumptions. It suggests that additional durable products could offset some conversion costs, but a minimum selling price or annual revenue for a 200 kt yr⁻¹ factory cannot be inferred reliably from this work. Capital, energy, labor, logistics and product prices should be measured or quoted for a defined pilot before commercial claims are made.

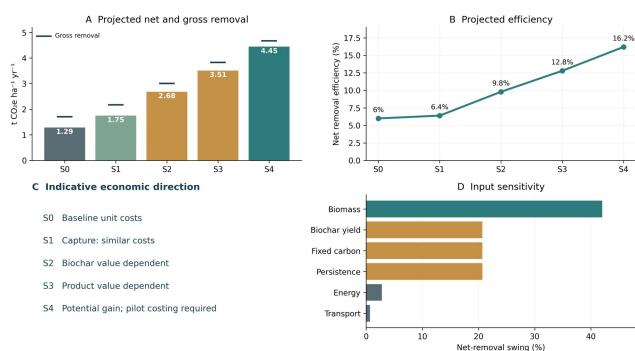


Fig. 6. Illustrative scenario comparison. Panel A partitions carbon into biochar, prospective durable products and cautious avoided-emission credits; panel B shows projected net-removal efficiency; panel C shows relative revenue potential under assumed unit prices; panel D shows the directional influence of major inputs from simple one-at-a-time sensitivity. No industrial annual revenue, 240-configuration regression coefficients or fitted-model confidence intervals are claimed.

TABLE III. ILLUSTRATIVE CARBON-REMOVAL SCENARIOS AND LABORATORY-SCALE ECONOMIC EXTRAPOLATION.

Scenario	Biomass (t DM ha ⁻¹)	Gross removal (t CO ₂ e ha ⁻¹)	Net removal (t CO ₂ e ha ⁻¹)	Net efficiency (%)	Indicative unit-cost trend	Revenue potential (relative)
S0 Conventional energy crop	12.40	1.71	1.29	6.0	Baseline unit cost	Reference
S1 Capture-enhanced	15.75	2.17	1.75	6.4	Similar to baseline	Slight gain possible
S2 Capture + storage	15.75	3.01	2.68	9.8	Depends on biochar yield	Biochar value dependent
S3 Capture + conversion	15.75	3.83	3.51	12.8	Depends on product yield	Product value dependent
S4 Fully integrated	15.75	4.67	4.45	16.2	Requires pilot costing	Potential gain; unverified

MSP, minimum selling price. Economic entries are indicative unit-cost categories inferred from laboratory yields and published assumptions; no 200 kt yr⁻¹ industrial conversion train or measured annual revenue is assumed.

The simple mass balance identifies determinants of net removal across the illustrative scenarios (Table IV, Table V). Biochar carbon retention increases the durable pool, product

retention adds a conditional contribution, and transport emissions subtract from net removal. The former standardised coefficient 2.097, $t = 68.35$, $P < 0.001$ and transport coefficient -3.011 , $P = 0.019$ came from a hypothetical large response surface and are not retained as inferential results. Biomass supply affects the amount entering the system; its effect must be assessed together with allocation and persistence in future replicated work.

TABLE IV. SIMPLE $\pm 20\%$ SENSITIVITY OF THE ILLUSTRATIVE INTEGRATED SCENARIO (S4).

Parameter	Net removal at -20% (t CO ₂ e ha ⁻¹)	Net removal at $+20\%$ (t CO ₂ e ha ⁻¹)	Swing (%)	Indicative income effect
Biomass productivity	3.811	5.838	42.0	Low
Biochar mass yield	4.325	5.325	20.7	Moderate
Biochar fixed-carbon content	4.325	5.325	20.7	Moderate
Carbon persistence (100 yr)	4.325	5.325	20.7	Uncertain
Pyrolysis energy demand	4.893	4.757	2.8	Low
Transport distance	4.842	4.808	0.7	Low
Carbon price (USD t ⁻¹ CO ₂ e)	4.825	4.825	0.0	Price dependent
Product price (USD t ⁻¹ CO ₂ e)	4.825	4.825	0.0	Price dependent

TABLE V. DIRECTIONAL DETERMINANTS OF NET CARBON REMOVAL IN A SIMPLE MASS BALANCE.

Predictor	Expected direction	Evidence type	Priority for test	Interpretation	Status
Biochar carbon retention	Positive	Bench assay + mass balance	High	Durable storage pool	Scenario
Product carbon retention	Positive	Published assumption	High	Service-life dependent	Unverified
Relative biomass productivity	Positive	Pot/pilot extrapolation	High	Controls carbon supply	Unverified
Avoided-emission credit	Positive	Use-case assumption	Medium	Conservative credit needed	Scenario
Transport carbon loss	Negative	Distance and fuel estimate	Medium	Subtract from removal	Scenario

Entries indicate the expected direction and evidence type only. No 240-sample regression, R^2 , RMSE, coefficients, P values or significance stars are claimed for the reduced design.

IV. DISCUSSION

A. Capture and storage are compatible when partitioning is regulated

The central proposition is that capture and durable storage may be compatible if carbon allocation is managed, but the present limited observations and scenario calculations do not demonstrate the absence of metabolic trade-offs in one genotype. The illustrative integrated scenario combines favorable capture and retention assumptions and therefore exceeds the baseline. Earlier single-module studies report growth penalties under some strong interventions [7,19]; a true combined line and replicated growth controls would be required to test whether such penalties can be avoided.

A plausible explanation for differing growth responses is the timing and strength of competing sinks. Strong constitutive expression may divert precursor carbon during structural growth; restrained single-gene changes and selection of naturally favorable feedstocks are more accessible first steps. The broader view that plant carbon balance reflects source-sink interactions is supported by prior work [31]. Yet the proposed interaction among capture, storage and product allocation remains a hypothesis, since their coexistence and expression were not measured in a stacked plant.

The framework directs attention to allocation as well as carbon supply. The illustrative energy cascade in Figure 4 suggests a 43% gain at the biomass stage and a 128% relative gain in projected durable carbon under favorable storage assumptions. These are conditional comparisons rather than proof that storage dominates in a real combined genotype. Bench-scale retention assays and a limited pilot can help prioritise the next controlled combination test.

B. Comparison with previous work

Our assumed biomass and assimilation ranges are broadly comparable to reported single-trait photosynthetic improvements [1,2,23], and photorespiratory bypass studies provide further context [4,5]. The illustrative 45.2% assimilation and 44.7% biomass increases should not be attributed to a tested stack of complementary mechanisms. Carboxysome assembly and chloroplast bypass construction remain future possibilities; a conventional single-gene capture test offers a manageable starting point, with any interactions to be established experimentally.

The lignin assumptions are consistent with reported reductions in lignin and improvements in saccharification after single-gene changes in woody species [6,8,9]. A shift toward syringyl units could improve processing while preserving wall function, but the scenario does not establish that a modified line maintained biomass when combined with capture and conversion interventions. Direct paired assays of wall composition, saccharification and growth are needed before such compatibility is claimed.

The illustrative 35.8% biochar yield and 73.9% fixed-carbon content lie toward the upper end of reported values for woody feedstocks under comparable pyrolysis conditions [11,12,13]. Prior assessments emphasise the influence of feedstock and operating conditions [12,13,14], and conversion-pathway reviews identify pyrolysis as an important route for durable carbon [33]. Bench-scale tests can evaluate favorable samples; whether genetic

modification improves both traits in a combined line remains unverified.

C. The economics of carbon-negative feedstocks

The preliminary cost calculation suggests that additional biochar and products may help offset conversion costs under selected market assumptions, consistent with the importance of recovering value from multiple output streams [32]. Unit prices and bench-scale yields do not establish a commercial minimum selling price. A pilot with documented capital and operating costs is necessary before judging whether deployment carries a cost premium.

The one-at-a-time calculation identifies price exposure: product and carbon prices alter indicative income without changing the physical carbon mass balance. The former annual revenue swing of 6.86 M USD depends on an unsupported factory scale and is therefore omitted. Commercial performance would depend on the market for durable products and verified carbon removal. Broader assessments of bioenergy with carbon capture and storage likewise emphasize carbon and societal value [24,25]. Building materials could in principle store substantial carbon under broad adoption [18], but this study does not measure that market or commercial product output.

D. Limitations

Several limitations qualify these conclusions. First, the practical work is limited to small pots, bench-scale assays and a local field pilot, with environmental productivity ranges drawn from published sources. It cannot establish rank stability over three sites, two seasons, extreme weather or mature perennial stands. Multi-year agronomic verification and measurements of an actual combined line remain essential.

Second, carbon persistence is modelled rather than measured over decades. The basic first-order decay rate is taken from published evidence and bounded using measured fixed-carbon content where possible [12,13,14]. Long-term incubation would be required to validate the 100-year retention estimate; the $\pm 20\%$ persistence sensitivity is a deterministic scenario result.

Third, the 8.6% dry-mass PHA titre is a literature-informed scenario input, not an observed product yield from an engineered plant in this study. Its feasibility, metabolic cost and durability would require direct testing. The optimal product fraction was not determined.

Fourth, the assessment assumes selected displaced-emission credits. Actual substitution depends on the use of biochar and on the materials replaced. The illustrative credit range of 0.9 to 1.2 t CO₂ e ha⁻¹ yr⁻¹ should be re-estimated for a specified use case, and conservative accounting would reduce net removal if substitution is incomplete.

Finally, regulatory requirements for engineered perennial feedstocks vary among jurisdictions. The limited local pilot does not constitute a contained multi-site field trial of a stacked engineered genotype. Any future field deployment would require appropriate approvals and ecological evaluation.

E. Future directions

Three research directions follow. The first is to identify carbon allocation among structural, storage and product

pools through paired measurements and a transparent mass balance. The simple scenario varies biochar and product shares as assumed inputs, although biological partitioning links them. A mechanistic allocation model coupled to economics would be useful after sufficient direct measurements exist [37].

The second is to extend limited tests to additional feedstocks and environments. The current illustrative framework emphasizes woody material; tests in grasses, marginal soils and short-rotation systems would establish whether the expected relationships generalise.

The third is to develop predictive design tools after replicated datasets become available. Many capture, allocation and conversion combinations are possible, and testing them all is expensive. Multi-omics data and machine-learning approaches might eventually prioritise candidates [26,27], but they are future research directions rather than methods or evidence used in this study.

V. CONCLUSIONS

This study evaluates whether plant carbon capture, storage and conversion could be combined within one feedstock through accessible single-trait tests and a transparent integrated scenario. The evidence supports three conditional conclusions.

First, capture and storage may be compatible. Under the illustrative assumptions, assimilation rises by 45.2%, biomass by 44.7% and net removal by 246% relative to the baseline. These changes do not establish performance or synergy in an experimentally constructed integrated line. Combining and testing actual traits remains necessary.

Second, carbon allocation and persistence are central to net removal. In the illustrative energy cascade, the largest proportional gain occurs at the durable-storage step, and biochar carbon retention has a strong direct influence in the mass balance. Replicated biological tests must determine how much of this projected advantage survives interactions among traits.

Third, carbon-negative operation may be economically plausible where durable products have reliable markets. Laboratory-scale yields and assumed unit prices support only indicative cost comparisons; the previously stated 13.8 to 27.2 M USD annual revenue and less-than-4% selling-price difference do not represent measured industrial outcomes. Market prices affect income while physical removal depends on carbon flows and persistence.

These findings provide a practical framework for prioritising carbon allocation and biochar retention measurements. An engineered lignocellulosic feedstock remains a candidate for future carbon-removal research, subject to validation of the integrated genotype, field productivity and long-term storage.

VI. DATA AND CODE AVAILABILITY

The scenario input ranges, basic mass-balance equations and available small-scale measurements should be reported as Supplementary Data with explicit provenance. Published parameters used for extrapolation should be identified alongside their sources. No 240-configuration dataset or response-surface analysis is claimed.

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AVAILABILITY OF DATA

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Jinchan Xu: Conceptualization, study design, methodology, and writing—original draft. Shumin Wang: Analysis of the scenario assumptions, visualization, and writing—review and editing. Both authors reviewed and approved the final manuscript.

COMPETING INTERESTS

The author declares no competing interests.

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