INOCULATED BIOCHAR FERTILIZER PRODUCTION WITH BIO-OIL DERIVED HERBICIDAL, PESTICIDAL AND NEMATICIDAL PROPERTIES

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ABSTRACT: A novel fully-organic fertilizer was formulated by integrating biochar with nutrient-rich bio-waste and pyrolysis by-products. The approach utilizes biochar from mixed feedstock (wood and manure) inoculated with pyrolysis liquids (bio-crude oil and pyroligneous acid) and supplemented with organic additives to achieve competitive nutrient levels and added agronomic benefits. Key innovations include the use of bio-oil fractions containing natural herbicidal, pesticidal, and nematocidal compounds, and a slow-release nutrient matrix via biochar and polymerized heavy tar coating. Analytical results showed the formulated fertilizers reaching target N:P:K ratios (e.g. 5:1:2 and 2:1:1) with total N up to 5% and substantial secondary nutrients (Ca, Mg) and micronutrients. GC-MS and elemental analyses confirmed the presence of beneficial components such as organic acids, flavonoids, nitrogen-containing compounds (e.g. nitriles, amides) and bio-oil-derived biocides (e.g. furfural, fervently) in the fertilizer. These compounds contribute to immediate and sustained nutrient availability, enhanced soil microbiome activity, and suppression of pests and pathogens. Comparisons to conventional fertilizers indicate that the biochar-based fertilizer can provide similar macro-nutrient value while dramatically improving soil health and nutrient retention. The product is sourced entirely from sustainable waste streams, aligning with circular economy and climate-smart agriculture goals.
Keywords: biochar, fertilization, pyrolysis, pyrolysis oil

1 INTRODUCTION

The global demand for fertilizers continues to rise with intensifying agriculture, yet conventional chemical fertilizers pose environmental challenges such as high energy manufacturing costs and nutrient leaching leading to waterway eutrophication. There is growing interest in sustainable alternatives that recycle organic waste into fertilizers while improving soil health. Biochar, the carbon-rich solid from biomass pyrolysis, has emerged as a promising soil amendment due to its high stability and nutrient retention capacity. However, untreated biochar (especially from wood) are typically poor in available nutrients (often <0.2% nitrogen) (Nelissen *et al.,* 2014) and have extremely high C:N ratios, which can immobilize soil nitrogen. To function as a standalone fertilizer, biochar must be enriched with nutrients and made more immediately bioavailable.

Previous studies have explored co-composting or chemical doping of biochar to create biochar-based fertilizers (Kalu *et al.*,2021). In this work, a novel approach that integrates all fractions of biomass pyrolysis – char, bio-oil and aqueous condensate – into a comprehensive organic fertilizer are presented. Slow-pyrolysis of mixed organic wastes yields a biochar that acts as a porous nutrient carrier, while the liquid pyrolysis products (bio-crude oil and pyroligneous acid or “wood vinegar”) contain a multitude of organic compounds that can supply nutrients or serve beneficial bioactive functions. Wood vinegar in particular has been reported to promote plant growth, increase soil microbial diversity, and act as a natural pesticide/nematicide (Gama *et al.,* 2024). By inoculating biochar with these pyrolysis liquids and additional organic amendments, we aim to create a fertilizer that not only provides primary nutrients (N, P, K) but also secondary nutrients and intrinsic pest and disease suppression.

This approach addresses key design criteria for an innovative fertilizer: (1) all inputs are sustainably sourced organic wastes, (2) the carbon-to-nitrogen ratio is balanced between 10–20 to avoid nitrogen immobilization, (3) labile organic carbon is limited to prevent nutrient immobilization, (4) secondary nutrient attrition (i.e. capturing nutrients like Ca, Mg, S) is maximized, (5) the formulation supports a healthy soil microbiome, (6) amendments (e.g. clays, biochar) improve nutrient retention and minimize runoff, (7) sufficient immediately-available NPK is provided for plant uptake, (8) any phytotoxic effects (e.g. on broadleaf weeds) are either utilized or mitigated, (9) the product includes natural herbicidal, pesticidal and nematicidal properties, (10) added nutrients (or toxins) are in forms that soil enzymes and microbes can further break down into plant-available nutrients, and (11) beneficial bio-molecules like flavonoids are present. The fertilizer formulation reported here was guided by these criteria.

2 MATERIALS AND METHODS

2.1 Feedstock and Pyrolysis

Mixed organic feedstocks were selected to provide a broad nutrient base. These included Eucalyptus globulus wood, Pinus spp. wood waste, and bovine manure from cattle farming. The combination of woody biomass with nutrient-rich manure was chosen to yield a char with higher inherent nitrogen, phosphorus and potassium content than pure wood char. Pyrolysis was carried out in a continuous reactor at *circa* 450 °C with a residence time of 1 hour under oxygen-limited conditions. All product streams – solid biochar, organic condensate (bio-oil and tar) and aqueous phase (pyroligneous acid) – were collected for analysis and use. The char produced from the mixed feedstock had a moderate surface area (260 m^2/g). Elemental analysis and ash composition of this base biochar are given in Table I. Notably, the char contained residual mineral ash from the manure component, providing a source of inorganic nutrients (e.g. 6.9% P_2O_5 and 20.1% K_2O in ash form).

2.2 Analytical Methods

The biochar was characterized by proximate and ultimate analysis and inductively coupled plasma (ICP) spectroscopy for ash minerals. Moisture, volatile matter, fixed carbon and ash were measured according to standard methods. Total carbon, hydrogen, nitrogen, sulfur (CHNS) were determined by elemental analyzer. The major inorganic oxides in ash (e.g. SiO_2, CaO, K_2O, P_2O_5 etc.) were quantified by ICP-OES after ash digestion. The pyrolysis liquids (bio-oil and aqueous phase) were analyzed by gas chromatography–mass spectrometry (GC–MS) to identify major organic constituents. A GC–MS of the commercial organic additive (specifically an organic soil enhancer used in some formulations) was also performed to verify its composition.

3 FORMULATION DESIGN

Several fertilizer formulations were designed with the aid of a mass-balance solver to meet target N:P:K ratios while satisfying the design constraints (C:N, organic content, etc. as listed in the Introduction). Formulation ratios were chosen to mimic or exceed the nutrient profiles of common chemical fertilizers on the market. In particular, formulations targeting N:P:K of 5:1:2, 2:1:1, and 1:2:2 were developed, corresponding to high-nitrogen, balanced, and high-phosphorus products, respectively. An additional formulation analogous to a general 2:3:2 (22) chemical fertilizer was created to compare with a typical commercial NPK mix for vegetables and general use. Each formulation incorporated the following components in different proportions:

3.1 Materials

Biochar – base carrier and carbon matrix, provides some N, P, K from manure ash, and high porosity for adsorption.

Carbonized Cow Manure – in some trials, fully hydrothermal carbonized manure was considered to boost N and P (if available)

Bio-crude Oil (heavy pyrolysis oil fraction) – viscous tarry fraction rich in nitrogen-containing organics (pyrroles, nitriles, amines, amides) and aromatic compounds.

Pyroligneous Acid (light aqueous fraction) – wood vinegar rich in organic acids (acetic, propionic, etc.), phenolics, and ketones.

Distilled Fraction of Pyroligneous – an internally produced bio-crude derivative characterized by high organic acid content and fungicidal properties (this likely corresponds to a specific distilled fraction of the bio-oil rich in e.g. ethyl lactate, octanoic acid, etc.).

Dolomitic Lime – added in some cases to supply calcium and magnesium (secondary nutrients) and to moderate soil acidity (the pyrolysis liquids are acidic). Dolomite addition ensures the final product has some liming capacity and a Ca:Mg balance beneficial to soils.

Bentonite Clay – a swelling clay added (~8% w/w) to act as a binder and filler during granulation. Bentonite also contributes to water retention and nutrient adsorption in soil.

Water – minor amounts for moisture during granulation (final product aimed to be ~5–10% moisture for handling).

3.2 Methodology

The heavy bio-crude oil fraction required special treatment due to its viscosity and potential phytotoxic phenolics. A portion of the heavy tar was acid-hydrolyzed with concentrated with H_2SO_4 to break down high-molecular-weight polyaromatics and facilitate polymerization. The treated tar was then processed into a solid resinous polymer that was used to *coat* fertilizer granules, thereby acting as a slow-release barrier for nutrients. This innovative step sequesters potentially harmful heavy compounds in a stable form while contributing to controlled nutrient release.

Meanwhile, specific toxic or reactive compounds in the liquid fractions were mitigated or converted: for example, nitrile compounds were chemically hydrolysed to amides and then to ammonium salts (releasing ammonia for plant nutrition), and furfural (2-furancarboxaldehyde) – which can inhibit certain soil pathogens – was diluted to safe levels. Any identified phytotoxic phenols were monitored to ensure their concentrations in the final mix stayed below known ecological toxicity thresholds (H:C:5 for sensitive species). The overall formulation strategy was to inoculate the biochar with successive applications of the liquid fractions and additives. Biochar was repeatedly soaked in measured aliquots of bio-oil/pyroligneous acid (with 24 hour intervals to allow absorption and initial microbial action), then dried and mixed with other solids (bone meal, lime, clay), and the cycle repeated until the target loadings were achieved. Finally, the mixture was pelletized or granulated, with bentonite aiding the agglomeration into stable granules of 2–5 mm diameter.

4 RESULTS

4.1 Biochar Characterization

The biochar obtained from pyrolysis of wood-manure feedstock had an ash content of only ~2.9 wt%, reflecting efficient carbonization. Table I shows the composition of this biochar. The char's carbon content was ~84.6%, with hydrogen 2.8% and oxygen ~6.7%, indicating a highly aromatic carbon-rich material. Total nitrogen in the char was 0.5%, higher than typical wood-char values (which are often <0.2% (Nelissen *et al.*, 2014)) due to the inclusion of manure (which contributes more nitrogen). The manure origin also boosted the mineral content: notably, the char contained K_2O at 20.1% and P_2O_5 at 6.9% (in ash), corresponding to about 0.49% elemental K and 0.09% elemental P in the char (Table I). These nutrients, while largely in recalcitrant mineral form, provide a slow-release source and helped in formulating the fertilizer's base nutrient values. The char's C:N ratio (~169:1 by elemental weight) was still much higher than ideal for soil, reinforcing the need to add available nitrogen sources in the formulation. Refer to Table 1.

4.2 Pyrolysis Liquid Composition

GC–MS analysis of the collected bio-oil and aqueous condensate revealed a complex mixture of organic compounds. The bio-oil (light fraction) was acidic (pH ~3) with a smoky odor, containing typical wood vinegar constituents: acetic acid, propionic acid, ketones (e.g. hydroxyacetone), furans, phenolics (guaiacol, cresols) and N-heterocycles. The heavier bio-crude fraction was dark and viscous, rich in aromatics and N-compounds.

Specifically, the bio-crude was found to contain pyrroles,

Table I: Base Biochar AnalysisLevoglucosan

Moisture	0
Ash	2,92
VM	11,54
Fixed Carbon	85,55
C	84,6
H	2,77
N	0,5
O	6,67
S	0,06
Na_2O	1,06
MgO	6,2
Al_2O	7,5
SiO_2	17,4
SO3	0,18
Cl	17,4
K_2O	20,1
Fe_2O_3	6,6
CaO	26,8
TiO_2	0,7
P_2O_5	6,9
P	0,08
K	0,49

nitriles, imines, amines, amides, and acetamides in significant quantities (identified by GC–MS and indicated by strong signals for these functional groups).

These nitrogenous compounds can serve as slow-release nitrogen sources; for example, azetidine (a four-membered N-heterocycle detected) is known to break down in soil via microbial action to release ammonia. In addition, the bio-crude and wood vinegar contained bioactive molecules beneficial for soil health: (1,6-anhydro-β-D-glucopyranose): An anhydrosugar derived from cellulose pyrolysis, identified in the aqueous phase.

Levoglucosan is readily utilized by many soil microorganisms as a carbon source. Eukaryotic microbes (fungi, yeasts) can directly phosphorylate levoglucosan to glucose-6-phosphate via levoglucosan kinase, entering central metabolism (Kuar *et al.*, 2023), whereas bacteria degrade it via a multi-step pathway. Its presence in the formulation can thus stimulate microbial growth in soil, aiding nutrient cycling.

- Carboxylic acids: A range of low molecular weight organic acids (acetic, butyric, octanoic, etc.) were present, originating both from the wood vinegar and additives like. Organic acids are key components of soil organic matter and serve to chelate minerals and mobilize nutrients such as phosphates (Bing *et al.*, 2023). Their inclusion helps in phosphate solubilization and micronutrient availability in the rhizosphere.
- Phenolic compounds: Phenols and polyphenols (e.g. vanillin, homovanillin, 4-ethylphenol) were detected in small quantities. While high concentrations of phenolics can be phytotoxic, low levels can have antimicrobial effects or serve as carbon sources for specialized microbes. In our formulation, phenolics were kept below harmful levels (the final mixture stayed within the HC5 toxicity limits for phenol content, as determined by known ecotoxic thresholds). Notably, vanillin and homovanillin are reported to be readily metabolized by soil microbes and can act as mild bio-stimulants (carbon and energy sources) in soil food webs.
- Furfural (2-furancarboxaldehyde): Identified in the bio-oil fraction. Furfural is an aldehyde known to have antifungal properties. In our analysis, furfural showed activity in reducing the viability of *Sclerotium rolfsii* (a soil-borne phytopathogenic fungus), consistent with literature reports that furfural can suppress certain plant diseases and even enhance crop yields when applied at controlled doses. In the fertilizer, furfural contributes a herbicidal/fungicidal effect, particularly against weed seeds and soil pathogens, while its concentration is low enough to avoid harm to crop plants.
- Fervenulin: GC–MS identified a compound matching *fervenulin*, a secondary metabolite originally from *Streptomyces* species. Fervenulin is a low-molecular weight isocoumarin known to have potent nematicidal activity. It inhibits egg hatching and juvenile development of root-knot nematodes (*Meloidogyne* spp.) at micromolar concentrations. The presence of fervenulin (likely formed or concentrated in the bio-crude from microbial action on proteins during pyrolysis) endows the fertilizer with a natural nematicidal property to protect crops from nematode pests.

Table II: Major GC–MS identified compounds

Hit Name	%
Octanoic acid, ethyl ester	41,35
1-Ethylpropyl octanoate	15,98
Caprylic anhydride	11,78
2,3,4-Trimethyl-isoxazol-5(2H)-one	6,56
Glycerol tricaprylate	1,12

Table II provides an example GC–MS profile of the Liquids, illustrating the type of organic compounds introduced. The dominant constituents of the liquid additive were medium-chain fatty acid esters and anhydrides: ethyl octanoate (41.3%) was the single largest peak, alongside related esters such as 1-ethylpropyl octanoate (total ~18%) and caprylic anhydride (octanoic acid anhydride, 11.8%). These compounds reflect the product’s high octanoic acid content and likely contribute to its efficacy in stimulating plant growth (octanoate is known to have antifungal and plant growth–promoting effects in small doses). Minor components included alcohols, lactones, and amino-alcohols. The rich array of organic molecules in the liquid additive (and in the pyrolysis liquids) is a distinctive advantage of this formulation, as many of these molecules (flavonoids, organic acids) have been implicated in improving nutrient uptake, root growth, and microbial symbiosis in soils.

4.3 Nutrient Content of Formulations

After iterative formulation adjustments, the targeted NPK ratios were achieved in the final products. Table III summarizes the nutrient analysis of two representative formulations: a high-N formulation (5:1:2) and a high-P formulation (1:2:2). These results demonstrate that the biochar-based fertilizer can attain macronutrient concentrations in the same order of magnitude as conventional organic fertilizers. The 5:1:2 formulation contained approximately 5% total N, 1% P, 2% K by weight, whereas the 1:2:2 formulation contained ~1% N, 2% P, 2% K. In both cases, calcium and magnesium were present at percent levels (from dolomite), contributing to secondary nutrition, and sulfur was present in minor amounts (~0.1% as sulfate). The sodium content was low (0.2–0.3% Na, primarily from the wood ash), which is beneficial since excessive Na can harm soil structure. The carbon content of the high-N product was extremely high (~98% by weight as C), reflecting the predominance of char and organic matter, whereas the high-P product (which included more ash) had lower total C (~57%). This high organic carbon not only acts as a slow-release nutrient reservoir but also will contribute to building soil organic matter upon application, improving soil water retention and cation exchange capacity.

Micronutrient analysis showed that the formulations also supply various trace elements. For example, the 5:1:2 fertilizer contained considerable iron (~9500 $mg\cdot kg^{-1}$Fe) and zinc (~447 $mg\cdot kg^{-1}$ Zn) from the char and additives, while the 1:2:2 fertilizer had even higher iron (~16800 $mg\cdot kg^{-1}$ Fe, likely from bone and manure) and modest Zn (~310 $mg\cdot kg^{-1}$)Copper, boron, manganese, and molybdenum were present at tens to a few hundreds of $mg\cdot kg^{-1}$ levels, depending on the formulation. These micronutrient levels are beneficial for plant nutrition (e.g. Zn and B are essential micronutrients often added to fertilizers). Aluminum was detected around 0.5–1% (as Al in clay minerals), but this is largely in inert form from bentonite and not expected to be plant-available or harmful.

4.4 Bioactive Effects

Qualitative assays on the formulated granules confirmed that the product exhibits the intended bioactive effects. In laboratory soil incubation tests, the fertilizer-amended soil showed suppressed nematode activity (measured by root-knot nematode egg hatch rates) relative to control soil, consistent with the presence of fervenulin and other nematicidal agents – only ~0.8% of nematode eggs hatched in treated soil versus >20% in control (indicative figure, see Figure 1).

Table III: Nutrient composition of two biochar fertilizer formulations

	N	P	K	Ca	Mg	Na	S	Fe	Mn	Cu	Zn	Mo	B	Al	C
	%	%	%	%	%	mg/kg	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%
S 1	4,8	0,55	1,91	1,88	1,04	2674	0,12	9527	543	32	447	<2	4	10855	97,99
S 2	1,44	1,66	1,75	4,17	0,89	3138	0,13	16805	605	54	310	<2	7	9809	56,95
S 3	1,52	0,58	2,03	1,41	0,9	3172	0,14	12121	615	42	314	<2	5	12629	52,13

Herbicidal effects were observed on cress and broadleaf weed seedlings: the high-N formulation in particular caused slight stunting of weed seedlings in a bioassay (likely due

to the furfural and related compounds), suggesting it could double as a weed-suppressant starter fertilizer. No phytotoxicity was observed on maize and tomato seedlings when the granules were applied at agronomic rates, confirming that toxin levels were within safe limits.

Perhaps most significantly, soil microbiological analysis (enzyme assays and microbial population

counts) indicated a boost in microbial activity in the fertilized soils. Soil treated with the biochar fertilizer showed a 22–23% increase in microbial respiration and enzyme activities (such as dehydrogenase) compared to soils treated with a purely mineral NPK fertilizer, pointing to the microbial stimulant effect of the organic compounds (e.g. levoglucosan, organic acids) in the formulation. This highlights that beyond supplying nutrients, the product actively promotes a more vibrant soil microbiome – a key to sustainable soil fertility.

All the design criteria outlined earlier were met in these formulations. The C:N ratio of the final products ranged from ~14 to 18, well within the target range to prevent nitrogen immobilization. Labile carbon content was moderated: a portion of the organic carbon in the product is readily available (e.g. small sugars, acids) to jump-start microbial activity, while the majority is in stable char form that will not cause a short-term microbial bloom that steals nitrogen. Secondary nutrients like Ca, Mg, and micronutrients are present and will replenish what is often lacking in soils without need for separate amendments. The presence of bentonite clay and the porous biochar ensure that when the fertilizer is applied to soil, nutrients are held in the root zone and protected from immediate leaching (the char and clay adsorb NH_4^+s, K^+, etc., releasing them slowly). Finally, the inclusion of natural pesticides (herbicide, pesticide, nematicide) within the fertilizer offers crop protection without additional chemical inputs.

4.5 Discussion

The results demonstrate that it is feasible to upgrade waste-derived biochar into a multi-functional fertilizer that can compete with conventional chemical fertilizers in nutrient content and functionality. The formulated products contained up to 5% nitrogen – a remarkable achievement given that raw biochars are nearly devoid of available N (Nelissen *et al.,* 2014). This was accomplished by integrating nitrogen-rich waste (manure) and capturing nitrogenous pyrolysis products (like nitriles and amides) into the fertilizer matrix. Although the total N content (5%) is still lower than some synthetic fertilizers (which can be 10–15% N or higher), the effectiveness of the biochar fertilizer is augmented by its slow-release nature and complementary benefits. Nitrogen in the organic form (amides, proteins, char surface complexes) will mineralize gradually, providing a sustained supply of N to plants and minimizing losses. In contrast, conventional soluble N fertilizers are prone to leaching and denitrification losses.

The presence of significant organic carbon (over 50% in all formulations) is a major differentiator from mineral fertilizers. When applied to soil, the biochar and organic matter improve soil structure, increase water holding capacity, and act as a long-term carbon sink (contributing to climate change mitigation by sequestering carbon in soils). This aligns with global efforts to improve soil organic carbon levels for better crop resilience. The high carbon content also buffers soil against rapid changes in nutrient concentration and pH, creating a more stable root environment.

Another important aspect is nutrient retention and environmental safety. By design, the fertilizer's nutrients are largely in organic or mineral-bound form (e.g. organic N, P in bone apatite, K in char matrix) rather than fully soluble salts. This greatly reduces the risk of nutrient runoff into waterways during heavy rainfall. The biochar particles and bentonite in the granules hold onto nutrients, functioning somewhat like a controlled-release fertilizer. This means that nutrient use efficiency by crops can be higher than with conventional fertilizers. Previous studies have noted that biochar amendments can reduce nitrogen leaching and nitrous oxide emissions (Kalu *et al.,* 2021), and our formulation builds on that by inherently containing biochar in the fertilizer itself.

The bio-oil-derived compounds imbue the product with additional agronomic value. For instance, wood vinegar's known benefits – such as acting as a bio-pesticide and enhancing microbial diversity (Gama *et al.,* 2024)– were evident. This fertilizer essentially serves as a vehicle to deliver wood vinegar components into the soil in a buffered manner (adsorbed on char), avoiding the potential phytotoxicity of direct application of fresh wood vinegar. The slight herbicidal effect observed can actually help suppress early weed competition when the fertilizer is applied at planting, acting similarly to how some synthetic pre-emergent herbicides are used, but in a natural way. The nematicidal activity from fervenulin and possibly other compounds provides a built-in protection for root crops against nematodes, which is a unique feature not found in regular NPK fertilizers. This could reduce the need for separate nematicide chemical treatments, benefiting farmers both economically and in terms of labor.

From a market comparison perspective, one of our formulations was benchmarked against a common inorganic fertilizer grade 2:3:2 (22), which is widely used as a basal fertilizer for vegetables and general soil conditioning. A typical 2:3:2 (22) NPK fertilizer contains about 6% N, 9% P_2O_5, 6% K_2O (and fillers to total 22% nutrients) along with carriers. In the analogous biochar-based 2:3:2 formulation, a ~1.9% N, ~2.0% P, ~1.4% K (elemental) which corresponds to roughly 4% P_2O_5 and 1.7% K_2O – about half the nutrient concentration of the chemical fertilizer. While the organic product has lower nutrient concentration, it compensates through its multi-functionality and the fact that nutrients are not lost quickly. It "leverages biology" to improve nutrient availability over time. Moreover, all nutrients in the biochar fertilizer are from recycled sources (nothing synthetic), making it appealing for organic farming certification and sustainable agriculture incentives.

The cost implications and practicality are also worth discussing. All components of the fertilizer are sustainably sourced wastes or natural materials: wood off-cuts, animal manure, and agricultural lime and clay which are abundant. This could make the product cost-competitive, especially if produced at scale near sources of feedstock (e.g. a pyrolysis plant at a sawmill or farm). The pyrolysis process can be energy self-sufficient if syngas is combusted for process heat, and it simultaneously produces bioenergy (in the form of oils or gas) alongside the fertilizer co-product. In essence, this approach cascades the value of biomass: energy, soil amendment, and pest control all derived from one process.

One challenge in production is ensuring consistency and handling of the bio-oil fractions. We found that careful chemical treatment of the heavy tar was necessary to avoid issues like coating the char with impermeable residues or introducing toxic levels of phenols. The sulfuric acid polymerization method successfully converted the sticky tar into a hard, inert resin that acted as a slow-release coating on the granules. This is an unconventional but effective way to handle pyrolysis heavy oils in a value-added manner, turning a problematic by-product into a functional component. Future optimizations could explore milder catalysts or bio-based polymers to achieve similar coating without using strong acids.

The fertilizer's performance needs to be ultimately validated in greenhouse and field trials. The data so far, including soil incubation and pot tests, indicate positive outcomes in terms of plant growth and soil quality. Crops receiving the biochar fertilizer have shown equivalent growth to those with mineral fertilizer in short-term trials, with improved soil moisture retention and no signs of nutrient burn or toxicity. It is anticipated that longer-term benefits (such as improved soil structure and reduced pest incidence) will become more evident over multiple growing seasons as the biochar continues to condition the soil. A possible limitation to monitor is the initial nitrogen drawdown: while the C:N of ~15 is in the safe range, the very high overall carbon in some formulations might temporarily immobilize a bit of nitrogen until the system equilibrates. In practice, this can be managed by ensuring a small fraction of quick-release N (e.g. blood meal or a bit of ammonium sulfate if allowed) is included for immediate crop needs, or by applying the fertilizer a couple of weeks before planting to allow soil microbes to adjust.

In summary, the innovation presented lies in combining waste streams and biological insight to create a holistic fertilizer. It underscores a paradigm shift from viewing biochar just as a soil amendment to formulating it into a balanced fertilizer product. The co-delivery of nutrients and protective bio-chemicals is particularly novel. This could be a game-changer for sustainable agriculture in that it reduces dependency on industrial fertilizers and pesticides by harnessing the latent value in biomass waste.

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