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Michael O. Alaka, Joseph K. Ogunjobi, Osaretin E. Omoruyi, Olugbenga O. Oluwasina & Labunmi Lajide

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Transforming Extracted Cashew Nut Shell into Biochar and its Application as Soil Amender for Jute Mallow (*Corchorus olitorius* L.) Cultivation

Michael O. Alaka ^{a,b}, Joseph K. Ogunjobi ^{a*}, Osaretin E. Omoruyi ^a, Olugbenga O. Oluwasina ^a
& Labunmi Lajide ^a

^a Department of Chemistry, The Federal University of Technology, Akure PMB 704, Nigeria

^b Lagos State University of Education, Ijanikin, Lagos PMB 007, Nigeria

* Corresponding Author

Email address: josephogunjobi@outlook.com, ORCID: 0000-0001-9276-7310

Abstract

This study addresses the environmental challenges posed by the waste generated during the extraction of cashew nut shell (CNS) liquid by proposing a sustainable repurposing method. Extracted CNS (waste) was pyrolyzed at varying temperatures to produce biochars, which were subsequently applied as soil amendments for the cultivation of jute mallow. Agronomic, proximate, physicochemical, mineral and antinutritional effects of the biochar and manure on the crop and soil were investigated. The produced biochars exhibited comparatively low volatile matter and ash contents, alongside high fixed carbon levels, indicating suitability for both soil amendment and energy-related applications with minimal environmental risk. Agronomically, biochar application alone increased number of leaves by ~50% compared to control. Post-harvest soil analysis revealed substantial improvements in phosphorus, organic matter, and nitrate contents. Proximate analysis of harvested jute mallow indicated increased protein content alongside reductions in ash and key antinutritional factors, particularly phytate and saponin. Although short-term biochar and manure application did not result in statistically significant changes in bulk soil physicochemical properties, they exerted pronounced positive effects on plant growth performance and nutrient dynamics. Overall, the findings demonstrate the potential of CNS-derived biochar as a sustainable soil amendment that enhances both soil quality and crop nutritional value.

Keywords: secondary waste valorisation; fluidized bed fast pyrolysis reactor; agronomy; antinutritional factor; manure; biomass processing

1 Introduction

Solvent extractions of cashew nut shell (CNS), a primary waste from cashew processing, are known to deliver valuable and functional renewable products such as anarcadic acid, cardol and cardanol. These chemicals serve as biobased feedstocks across several industrial and biomedical applications, including surfactants, plasticizers and lubricants ¹, coatings, adhesives and epoxy resins (anticorrosive & protective finishes) ², biomedical and pharmaceutical leads (antimicrobial, antioxidant, anticancer) ³. However, the extraction process is often accompanied by the generation of substantial waste. The residue remaining after oil extraction, referred to as extracted cashew nut

43 shell (ECNS), a secondary waste, is frequently discarded. This secondary waste, which typically constitutes 60–85%
44 of the total mass of the CNS, depending on the extraction method used ^{4,5}, continues to pose a significant
45 environmental challenge. In line with the growing global emphasis on valorising agricultural residues into industrial
46 value-added products, which supports responsible consumption and a circular economy, it is desirable to harness this
47 abundant waste stream. One of the most promising approaches is carbonization or pyrolysis of the secondary waste to
48 produce value-added carbonaceous materials such as activated carbon or biochar, and liquid and gaseous products,
49 depending on the processing conditions employed. Particularly, biochar is a durable carbon-rich substance made from
50 biomass that has undergone pyrolysis in the absence of oxygen. Biochar has been extensively reported as a viable
51 renewable energy source ⁶⁻⁹, a soil supplement that enhances fertility and regulates soil greenhouse gas emissions ¹⁰,
52 and a filtration medium for wastewater treatment ¹¹. The properties of biochar are influenced and determined by
53 various technological factors, primarily the temperature at which pyrolysis occurs and the type of feedstock used ¹².
54 This in turn leads to biochar products with a diverse range of physicochemical values for pH, specific surface area,
55 pore volume, cation exchange capacity, volatile matter, ash content, and carbon content. Pyrolysis at high temperature
56 favours the formation of biochar with a well-developed specific surface area, high porosity, pH, ash content, and
57 carbon content at the expense of cation exchange capacity and volatile matter content. The physicochemical
58 characteristics of biochar determine its potential use as an amendment to enhance soil quality ¹².

59 Biochar has been widely applied as soil amenders and enhancers ¹³⁻¹⁵. This is because of its proven ability to enhance
60 soil physical and chemical characteristics, stimulate plant development, boost crop output, sequester carbon from the
61 atmosphere-biosphere pool into the soil, decrease the utilization of inorganic fertilizers by farmers and mitigate
62 contaminations ^{16,17}. The key characteristics of biochar include its extensive surface area with several functional
63 groups, its rich nutritional content, and its ability to slowly release fertilizer ^{16,18}. Compared to compost, which breaks
64 down quickly in moist tropical soils, biochar decomposes at a slower rate in the soil due to its high level of resistant
65 carbon. The residence period of wood biochar is typically between 100 and 1000 years, which is approximately 10 to
66 1000 times longer than the residence times of most soil organic matter ¹⁷. Hence, incorporation of biochar into soils
67 has the potential to serve as a carbon sink and enhance the availability of soil nutrients for crop utilization, owing to
68 its superior capability for retaining and absorbing nutrients. Notwithstanding the technical and logistical challenges
69 associated with biochar production, transportation, and application, its use as a soil amendment has been widely
70 recognized as economically viable. Economic evaluations indicate that while biochar deployment involves initial
71 capital investment, the long-term agronomic and environmental benefits substantially outweigh these upfront costs ¹⁹.
72 Consequently, irrespective of the production method employed, the sustained improvements in soil health and crop
73 yield underscore biochar's cost-effectiveness and reinforce its potential as a sustainable soil management strategy.

74 Jute mallow, *Corchorus olitorius* (Linn), is a widely used edible vegetable in several African countries, particularly
75 in Nigeria. It is one of the most sought-after vegetables in the southwestern part of the country. Vegetables are crucial
76 due to their possession of vital nutrients that contribute to the development of human body systems. Vegetables in
77 Africa, particularly in rural areas of developing countries, are significant providers of both macro and micro nutrients.
78 This is particularly important given the main source of sustenance in these areas is starch-based cuisine ²⁰. The
79 cultivation of jute mallow requires essential macronutrients and micronutrients such as nitrogen (N), phosphorus (P),

80 potassium (K), magnesium (Mg), calcium (Ca), sodium (Na), and sulfur (S), which are often insufficiently available
81 in the soil ²¹. These nutrients play distinct physiological and biochemical roles and must therefore be supplied to the
82 plant in appropriate quantities to ensure optimal yield. Consequently, adequate fertilization is necessary to enhance
83 productivity. However, mineral fertilizers are often expensive, not readily accessible to smallholder farmers, and their
84 excessive application can lead to soil degradation and environmental pollution ²². To promote sustainable and
85 affordable jute mallow cultivation, alternative fertilization strategies are required. Biochars could serve as alternatives
86 to mineral fertilizers since they contain these vital nutrients needed for jute mallow cultivation. Recent studies have
87 demonstrated that the application of biochar can significantly enhance soil physicochemical properties, nutrient
88 uptake, and the growth and nutritional composition of various agricultural crops ^{23,24}. To further enhance the
89 effectiveness of biochar in improving soil quality, structure, and plant growth, the co-application of biochar with
90 organic amendments such as compost or manure is often recommended.^{25,26} While biochar alone contributes to
91 improved soil aeration, water-holding capacity, and long-term carbon sequestration, its immediate nutrient supply is
92 typically limited. Manure and compost, on the other hand, are rich sources of readily available nutrients and labile
93 organic matter but may be prone to rapid mineralization and nutrient losses. When applied together, biochar can adsorb
94 and retain nutrients released from manure, reducing leaching losses and increasing nutrient use efficiency.

95 Although a few studies have explored the use of biochar for remediating heavy metal-contaminated soils cultivated
96 with jute mallow ²⁷, vermicomposting with biochar involving jute mallow ²⁸, and the combined application of biochar
97 with inorganic fertilizers on jute mallow ²⁹, the direct effect of biochar application, particularly biochar derived from
98 CNS, as a soil amendment, has not yet been investigated for this crop. Previous reports have described the
99 carbonization of ECNS to produce adsorbents for heavy metal removal ³⁰, and the pyrolysis of CNS, the primary
100 cashew nut shell waste, to generate liquid fuels and energy products ^{31,32}. However, to the best of our knowledge, no
101 study has examined the pyrolysis of ECNS and its application as a soil amendment in jute mallow cultivation. Given
102 the abundance of this agricultural residue and the potential of biochar as a cost-effective and environmentally
103 sustainable alternative to mineral fertilizers, the present study investigates the pyrolysis of ECNS at various
104 temperatures to produce biochar. The study aims to elucidate the influence of pyrolysis temperature on the
105 physicochemical properties of the resulting biochars and to evaluate their preliminary effects on soil fertility and jute
106 mallow quality.

107

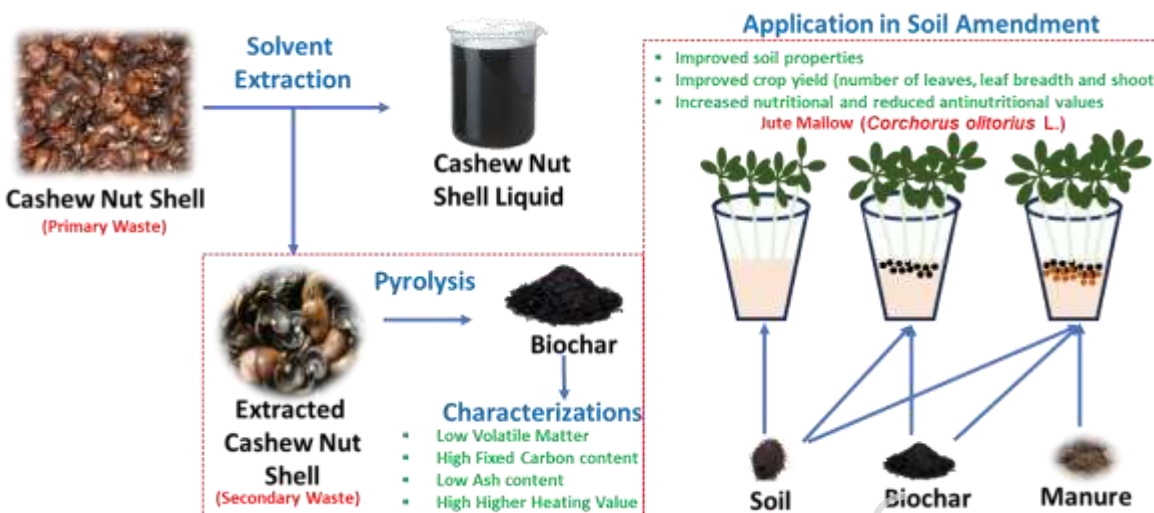
108 **2 Results and Discussion**

109 **2.1 Pyrolysis of ECNS**

110 Biochar production requires careful temperature control to tailor its properties for specific applications. Although
111 biochar can be produced across a wide temperature range (approximately 400–1000 °C), lower pyrolysis temperatures
112 are generally preferred for soil amendment due to higher biochar yields and favorable agronomic properties, while
113 higher temperatures are more suitable for applications such as catalysis and advanced materials. Accordingly,
114 appropriate temperatures were selected in this study to align with the intended soil application.

115 We have earlier reported the extraction of chemicals from CNS and how the extraction process can be achieved in

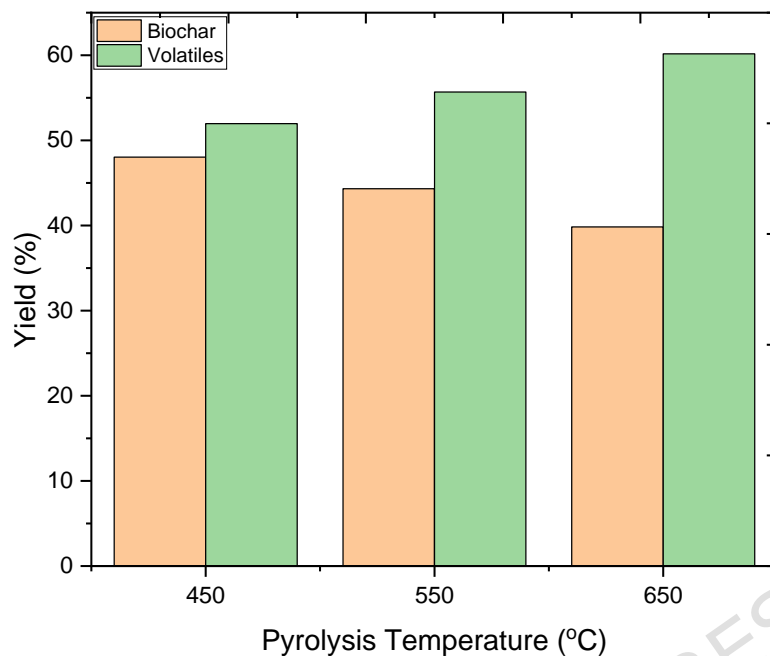
116 an environmentally friendly and sustainable manner⁴. ECNS, residue from the study, was subjected to pyrolysis at
 117 450 °C, 550 °C and 650 °C and the solid product utilized as soil amendment for jute mallow cultivation as shown in
 118 Figure 1.



119
 120 *Figure 1. Primary valorization of cashew nut shell to liquid chemicals and a further secondary valorization of*
 121 *the extracted shell to biochar which was subsequently applied as soil amender in the cultivation of jute mallow.*

122 Percentage yield and mass of ECNS biochar and volatiles evolved at temperature 450 °C, 550 °C and 650 °C was
 123 calculated after pyrolysis as shown in Figure 2. Results revealed that biochar yield decreased while volatile yield
 124 increased as pyrolysis temperature increased. This trend aligns with findings from other studies on biochar produced
 125 from various materials, including coconut shells³³, cogon grass³⁴, and pomegranate seeds³⁵. The reduction in biochar
 126 yield is attributable to a greater primary decomposition of the organic component of ECNS at higher pyrolysis
 127 temperatures^{36,37}. Additionally, secondary decomposition of the biochar residue, involving charring and
 128 devolatilization reactions, may have contributed to the yield decrease as the pyrolysis temperature increased³⁶. Overall,
 129 the highest biochar yield, 48.03%, was obtained at pyrolysis temperature of 450 °C while the lowest yield, 39.83%,
 130 occurred at 650°C.

131



132
133 *Figure 2. ECNS Pyrolysis product distribution as biochar and volatile at different conditions of temperatures*
134

135 2.2 Characterization of ECNS Biochar

136 Proximate, elemental analyses and energy value of ECNS and its corresponding biochars at different temperatures
137 were determined and presented in Tables 1 and 2 respectively.

138 *Table 1. Proximate Analysis of ECNS-based Biochar at Different Temperatures*

Pyrolysis Temperature	Moisture Content (%)	Volatile Matter Content (%)	Ash Content (%)	Fixed Carbon Content (%)
ECNS	1.10 ± 0.05	8.41 ± 0.07	3.1 ± 0.00	87.39
450 °C	0.37 ± 0.05	4.09 ± 0.18	5.68 ± 0.65	89.86
550 °C	0.12 ± 0.03	2.14 ± 0.18	7.63 ± 0.57	90.11
650 °C	0.08 ± 0.02	1.25 ± 0.11	9.26 ± 0.33	89.41

139
140
141
142 *Table 2 Elemental Analysis and Energy Values of ECNS Biochar at Different Temperatures*

Pyrolysis Temperature	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Sulphur (%)	HHV (MJkg⁻¹)
450 °C	41.80± 0.3	8.34 ± 0.2	0.40 ± 0.1	48.55± 0.6	0.15 ± 0.1	38.30
550 °C	43.82± 0.1	8.25 ± 0.3	0.39 ± 0.1	46.68± 0.2	0.12 ± 0.1	33.60
650 °C	44.29± 0.5	8.01 ± 0.3	2.37 ± 0.1	44.13± 0.2	1.20 ± 0.0	40.30

143

144

145 The moisture content of the ECNS was remarkably low and even lower for the derived biochars (<0.5%), decreasing
 146 further with increasing pyrolysis temperature. These values are considerably lower than those reported for coconut
 147 flesh waste biochar (CFWB), which ranged from 2.36% to 4.27%³⁸. This discrepancy may be attributed to differences
 148 in feedstock composition and the inherently hydrophobic nature of ECNS, which likely contributed to the
 149 exceptionally low moisture content observed.

150 The volatile matter (VM) content of ECNS was less than 10% and further decreased from 4.09% to 1.21% as the
 151 pyrolysis temperature increased from 450 °C to 650 °C. This reduction is expected, as higher pyrolysis temperatures
 152 promote the expulsion of volatile compounds from the biochar matrix³⁹. The VM values obtained were significantly
 153 lower than those reported for CFWB in the same temperature range (12.71–17.60%), indicating enhanced thermal
 154 stability of ECNS-derived biochars. The VM content is a critical parameter for assessing the quality and stability of
 155 biochar when applied as fuel or soil amendment⁴⁰. High VM content is generally undesirable, as it may reduce
 156 combustion efficiency and increase pollutant emissions during direct combustion⁴¹. For soil applications, Brassard et
 157 al.⁴², reported that biochars with higher VM contents tend to exhibit lower carbon sequestration potential. Therefore,
 158 the low VM values of ECNS biochars suggest that their application for energy generation and soil amendment would
 159 pose minimal environmental risk while offering greater carbon stability and sequestration efficiency.

160 The fixed carbon (FC) fraction represents the portion of biochar remaining after the release of VM, moisture, and ash,
 161 and it reflects the carbon available for energy conversion. Both the ECNS biomass and the resulting biochars exhibited
 162 high FC values (~90%), indicating substantial carbon content and energy potential. The ash content of biochar is a
 163 critical parameter influencing its suitability for various applications, particularly in agriculture and energy systems.
 164 Although no universal standard currently exists for acceptable ash levels in biochar, high ash content is generally
 165 considered undesirable⁴³. Excessive ash can negatively impact performance by altering the physicochemical
 166 properties of the material, reducing its adsorption capacity, and increasing the likelihood of residue accumulation
 167 during use. In soil applications, elevated ash levels may lead to undesirable shifts in pH or salt concentrations,
 168 potentially affecting nutrient availability and plant growth. Conversely, moderate ash content can contribute beneficial
 169 minerals such as potassium, calcium, and magnesium, which may enhance soil fertility when applied at appropriate
 170 levels. Therefore, optimizing ash content is essential to balancing the agronomic benefits of mineral enrichment with
 171 the potential drawbacks associated with excessive inorganic residues. The ash contents of ECNS biochars (Table 2)
 172 were notably lower than those reported for biochars derived from other biomass sources, suggesting that ECNS
 173 biochars are more likely to benefit soil with required minerals for plant growth⁶⁻⁸.

174

175 Elemental and energy analyses of the biochars using Elemental analyser revealed that they contain carbon, hydrogen,
 176 nitrogen, oxygen, sulfur, and could have higher heating value (HHV) up to 40.30 MJkg⁻¹ as presented in Table 2. As
 177 expected, the carbon content increased, while the hydrogen and oxygen contents decreased with increasing
 178 pyrolysis temperature. This trend can be attributed to the fact that, as the temperature rises, greater proportions
 179 of oxygen- and hydrogen-containing compounds are released in the gaseous and vapor phases, thereby reducing
 180 their concentrations in the resulting biochar and consequently enriching its carbon content⁴⁴. The low nitrogen
 181 and sulfur contents observed in the biochars indicate their environmental acceptability, as lower levels of these
 182 elements minimize the risk of releasing harmful emissions such as NO_x and SO_x during subsequent applications
 183⁴⁵. However, the biochar produced at 650 °C exhibited relatively higher nitrogen and sulfur contents compared
 184 with the others, which may be due to an increased surface reactions between char and volatile intermediates,
 185 leading to formation of nitrogen- and sulfur-containing compounds at this temperature^{46,47}. The HHVs recorded
 186 for the biochars were notably greater than those reported for biochars derived from plantain peels, corn cobs,
 187 rice straw, and Siam weed, suggesting superior energy potential⁶⁻⁸.

188 **2.3 Agronomic Effect of Biochar as a Soil Amender on Cultivating Jute Mallow**

189 Agronomic measurements were obtained from plants grown in control pots (soil + plant only; entry 1, Table 4) and
 190 from pots subjected to different treatments, namely soil + biochar + plant (labelled SB450, SB550, and SB650,
 191 corresponding to biochars produced at 450 °C, 550 °C, and 650 °C, respectively; entries 2–4, Table 4), as well as soil
 192 + biochar + plant + manure (labelled SBM450, SBM550, and SBM650; entries 5–7, Table 4).

193
 194 Several studies have emphasized the importance of combining biochar with organic manure to enhance soil fertility
 195 and plant performance. It has been reported that applying biochar alone often does not result in significant
 196 improvement in soil nutrient content^{25,48}. However, co-application of biochar with compost or manure enhances soil
 197 quality, stimulates plant growth, and produces a synergistic effect on soil nutrient dynamics under field conditions.
 198 This combined approach reduces dependence on synthetic fertilizers, enhances nutrient use efficiency, improves soil
 199 structure, and increases water retention capacity^{25,49-52}.

200
 201 The effects of biochar produced at different pyrolysis temperatures, both alone and in combination with manure, on
 202 the shoot length, root length, leaf breadth, and leaf number of jute mallow are presented in Table 3. Application of
 203 biochar alone led to increases in shoot length by 29.7%, 60.3%, and 31.6% for SB450, SB550, and SB650, respectively,
 204 relative to the control. When manure was co-applied with biochar, further enhancements of 57.2%, 14.3%, and 45.8%
 205 were observed for SBM450, SBM550, and SBM650, respectively.

206
 207 *Table 3 Agronomic, physicochemical, proximate and anti-nutritional analyses of soil, biochar and harvested jute*
 208 *mallow. Agronomic data were mean values of jute mallow at 4 weeks and 8 weeks.*

209
 210

Parameter	Soil alone	Soil + plant	SB450	SB550	SB650	SBM450	SBM550	SBM650
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alone								
<u><i>Agronomic Analysis</i></u>								
Shoot length (cm)	46.8±4.8	-	60.7±8.3	75±13.3	61.6±10.3	87.4±11.6	81.7±12.1	83.0±9.9
Leaf length (cm)	5.8±1.1	-	8.5±0.4	9.0±0.5	9.2±1.9	9.1±4.6	9.0±3.7	9.8±2.2
Leaf breadth (cm)	2.5±0.5	-	4.0±0.4	5.5±0.3	3.8±0.0	6.4±0.9	5.6±0.2	5.4±0.9
Root length (cm)	10.0±1.9	-	10.6±0.8	10.8±2.5	14.6±10.8	12.2±0.8	11.6±0.2	22.5±16.2
Leaf number	12.7±2.8	-	13.1±0.0	18.7±5.1	14.4±3.2	33.1±14.5	29.9±11.1	41±10.8
<u><i>Physicochemical analysis</i></u>								
pH	6.8±0.1	7.4±0.0	7.4±0.1	7.3±0.1	7.5±0.1	7.3±0.1	7.2±0.1	7.3±0.0
Organic Matter (g/kg)	8.4±0.2	11.3±0.2	17.2±0.2	19.4±0.2	16.0±0.2	22.2±0.2	28.1±0.6	22.5±0.2
Phosphorus (g/kg)	50.2±0.2	70.8±0.2	108.0±0.2	143.0±0.4	126.0±0.4	153.9±0.3	224.8±0.3	176.1±0.4
Nitrogen (g/kg)	0.2±0.0	0.3±0.0	0.5±0.0	0.6±0.2	0.3±0.2	0.7±0.0	0.9±0.2	0.7±0.0
Nitrate (g/kg)	51.2±0.2	63.2±0.3	82.2±0.2	85.5±0.2	60.8±0.2	88.5±0.0	113.6±0.2	97.0±0.5
CEC (c/mol/g)	9.1±0.0	8.4±0.2	8.5±0.2	8.6±0.0	8.6±0.0	7.9±0.1	8.6±0.1	7.5±0.1
<u><i>Proximate analysis</i></u>								
Moisture (%)	-	12.2±0.0	11.7±0.1	11.8±0.0	12.8±0.1	12.4±0.2	12.1±0.0	12.0±0.1
Ash (%)	-	10.3±0.1	9.7±0.1	9.3±0.2	9.7±0.3	10.5±0.1	9.5±0.1	9.8±0.1
Protein (%)	-	13.6±0.2	15.8±0.1	16.2±0.0	17.5±0.3	20.6±0.5	22.9±0.5	19.0±0.2
Crude Fibre (%)	-	12.6±0.1	13.4±0.14	14.4±0.1	12.2±0.0	13.5±0.1	14.1±0.1	13.9±0.0
Fat (%)	-	12.8±0.1	14.2±0.0	15.6±0.1	14.6±0.1	15.3±0.0	18.3±0.1	16.3±0.1
Carbohydrate (%)	-	39.0±0.3	35.3±0.0	32.5±0.3	32.6±0.2	27.6±0.5	23.1±0.4	30.0±0.2
<u><i>Anti-nutritional content</i></u>								
Phytate (mg/g)	-	33.0±0.1	14.8±0.3	17.3±0.5	15.7±1.1	5.8±0.1	8.2±0.2	8.2±0.1
Oxalate (mg/g)	-	3.8±0.8	2.3±0.0	3.2±0.0	2.8±0.1	1.2±0.0	1.9±0.0	1.7±0.0
Saponin (mg/g)	-	73.3±1.2	27.3±0.5	40.2±0.8	28.9±0.9	14.2±0.2	21.8±0.3	21.8±0.3
Tanin (mg/g)	-	2.9±0.0	2.7±0.1	2.9±0.1	2.9±0.0	2.4±0.0	2.7±0.1	2.6±0.0
Cyanide (mg/g)	-	0.9±0.0	1.9±0.0	0.7±0.0	0.9±0.0	1.6±0.1	0.3±0.0	2.3±0.1

211 The application of biochar markedly enhanced the leaf length of jute mallow plants. Without manure, all biochar
 212 treatments increased leaf length by 46.6–58.6%, while manure addition further raised this range to 56.9–68.9%,
 213 relative to the control (Table 3). Interestingly, in the SB550 treatment, manure addition did not cause a further increase,
 214 maintaining an enhancement of 55.2%, suggesting that biochar produced at 550 °C alone provided sufficient nutrient

215 and structural benefits for optimal leaf elongation.

216

217 A similar pattern was observed for leaf breadth, where SB450 increased breadth by 60%, and manure addition boosted
218 this to 156% (SBM450). SB550 enhanced leaf breadth by 120%, with only a marginal 4% improvement following
219 manure addition (SBM550). In contrast, SB650 showed a 28% increase with biochar alone and a substantial 116%
220 increase when combined with manure (SBM650). These results indicate that while biochar alone positively influenced
221 leaf expansion, the synergistic effect of manure addition became more pronounced at lower and higher pyrolysis
222 temperatures.

223

224 The mean number of leaves (Table 3) reflected a similar trend. SB550 increased leaf number by 47.2% relative to the
225 control, and manure addition further improved this by 88.2% (SBM550). However, SB450 and SB650 showed
226 significant improvements only with manure co-application, increasing leaf numbers by 160.6% and 222.8%,
227 respectively. Since the number of leaves is a major determinant of harvestable yield, these findings imply that
228 combining ECNS-derived biochar with poultry manure effectively enhances plant productivity through improved soil
229 fertility and nutrient cycling.

230

231 These enhancements can be attributed to several interacting factors. First, biochar improves soil porosity, aeration,
232 and water-holding capacity, creating a favourable rhizosphere environment that supports better root proliferation and
233 nutrient uptake^{53,54}. The cation exchange capacity (CEC) of biochar decreases with pyrolysis temperature, promoting
234 nutrient retention and reducing leaching losses⁵⁵. Consequently, the SB550 biochar likely provided an optimal balance
235 between nutrient availability and surface reactivity, facilitating efficient nutrient uptake and physiological
236 development in jute mallow.

237

238 Furthermore, biochar–manure co-application introduces a synergistic mechanism where manure contributes readily
239 available nitrogen, phosphorus, and potassium, while biochar serves as a nutrient reservoir, gradually releasing
240 nutrients and stabilizing organic matter⁵⁶. This combination also enhances microbial activity and enzymatic processes
241 involved in nutrient mineralization, further supporting plant growth. However, at higher temperatures (e.g., 650 °C),
242 excessive carbonization reduces surface functional groups and nutrient retention capacity, explaining the relatively
243 diminished agronomic effect of SB650 despite manure addition.

244

245 Overall, biochar produced at 550 °C (SB550) exhibited the most balanced physicochemical characteristics, including
246 adequate porosity, moderate surface oxidation, and high CEC, resulting in optimal growth responses even without
247 manure supplementation. This suggests that ECNS biochar produced at this temperature is particularly suitable for
248 jute mallow cultivation, offering a sustainable and cost-effective strategy for enhancing soil fertility and reducing
249 dependency on mineral fertilizers.

250

251

252 **2.4 Effect of Application of Biochar on Soil Quality**

253 The physicochemical properties of the soil used for cultivating jute mallow were evaluated to assess the impact of
254 ECNS biochar and manure amendments. Results revealed significant enhancements in soil phosphorus and nitrate
255 contents, which reached maximum increases of 102.0% and 35.4% in SB550, and 217.7% and 79.8% in SBM550,
256 respectively, compared with the unamended control (Table 3). These findings indicate that both ECNS biochar and
257 manure are rich sources of phosphorus and nitrates. The elevated post-harvest phosphorus and nitrate levels further
258 suggest improved nutrient retention, implying that the soil could support successive cultivation cycles without
259 substantial fertility loss.

260 Organic matter content was also substantially increased by 72.1% in SB550 and 148.4% in SBM550, which likely
261 enhanced soil structure, water-holding capacity, nutrient mineralization, biological activity, and water–air infiltration.
262 Additionally, biochar application slightly elevated soil pH from 6.8 to the mildly alkaline range (7.0–7.4), optimal for
263 most crop growth. Nitrogen content showed similar improvements, increasing by 78.8% in SB550 and 160.6% in
264 SBM550, attributable to biochar’s influence on nitrogen circulation, retention, and conversion dynamics. However,
265 CEC showed no marked enhancement following biochar and manure application. These observations are consistent
266 with previous studies, reinforcing the potential of ECNS biochar as a soil amendment for improving nutrient status
267 and overall soil quality^{57,58}.

268 **2.5 Effect of Biochar Application on the Quality of Harvested Jute Mallow**

269 The proximate composition of harvested *jute mallow* as influenced by ECNS biochar and manure amendments is
270 presented in Table 3. Protein content increased markedly by 28.4% with biochar application (SB650) and by 67.6%
271 with the addition of manure (SBM550) compared to the control. Similarly, fat content increased significantly by 21.7%
272 under SB550 and 43.0% under SBM550, while crude fibre content rose by 14.6% in SB550. Conversely, carbohydrate
273 and ash contents decreased by 15.6% and 9.6%, respectively, particularly in biochar-amended soils (SB550). These
274 findings suggest that ECNS biochar not only enhances soil physicochemical properties but also improves the
275 nutritional composition of the crop grown on it.

276 The observed modifications in crop mineral composition following biochar application can be attributed to
277 biochar’s well-established capacity to adsorb metal ions and modulate soil nutrient dynamics. Biochar’s porous
278 structure, high surface area, and functional groups enable it to retain and exchange cations, thereby influencing
279 nutrient availability in the rhizosphere. These properties often translate into enhanced soil fertility and improved
280 mineral uptake by crops. Essential macronutrients such as Ca, K, and Mg play key roles in plant growth^{59,60}.
281 Potassium is critical for photosynthesis, respiration, stomatal regulation, and enzyme activation, while
282 magnesium is a structural component of chlorophyll and participates in nucleic acid and protein synthesis. Jute
283 mallow is naturally rich in minerals such as Zn, Fe, P, and K, which contribute significantly to its nutritional and
284 dietary value⁶¹. The Atomic Absorption Spectrophotometry (AAS) results in this study, shown in Figure 3,
285 demonstrate that ECNS-based biochar can selectively influence the retention and uptake of these nutrients.
286 Biochar-amended soils (SB450) exhibited increased retention of Ca (15.8%), K (11.3%), and Zn (35.0%) relative
287 to the control, reflecting biochar’s ability to stabilize and hold these cations within the soil matrix. Conversely,

288 Mg and Fe retention decreased slightly with biochar and manure addition, suggesting potential competitive
289 interactions among cations or changes in soil pH affecting their solubility.

290 Patterns in nutrient uptake further underscore biochar's role in modifying nutrient flow from soil to plant. Uptake of
291 Mg and K generally increased with both biochar and manure co-application, indicating improved nutrient accessibility
292 and root absorption. Calcium uptake showed a modest rise (10.3%) only under SBM550, while Zn uptake reached its
293 maximum in SB550 and SBM550, likely due to enhanced Zn bioavailability and reduced immobilization. In contrast,
294 Fe and Mn uptake declined in most treatments, except for slight increases in SB650 and SB450, which may be linked
295 to temperature-dependent changes in biochar surface chemistry that influence micronutrient mobility.

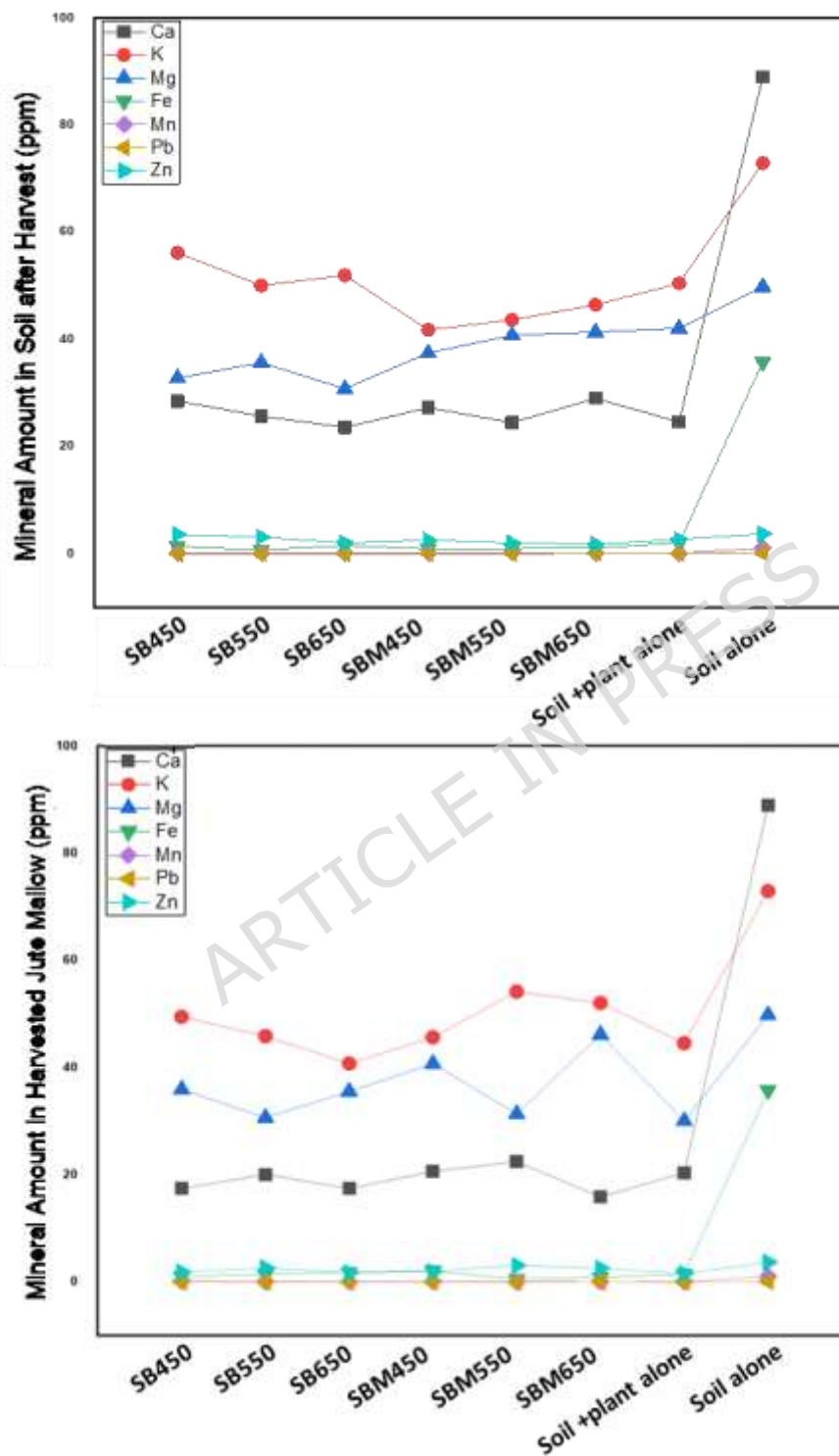
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300

301 *Figure 3 Effect of biochar and manure addition on the mineral content of the soil (top) and in the plant (bottom)*302 *after harvesting.*

303

304 Jute leaves are a staple leafy vegetable in many parts of Africa, particularly in Nigeria, where they are commonly
305 used to prepare a characteristic viscous soup. They are nutritionally valuable, being rich in vitamins, minerals, and
306 dietary fiber. However, their consumption is limited by the presence of antinutritional factors that reduce nutrient
307 bioavailability. The reduction of antinutritional factors is a critical indicator of improved crop quality, as these
308 compounds often limit nutrient bioavailability and may pose health concerns when present at elevated levels. In the
309 present study, the application of ECNS-derived biochar, produced at different pyrolysis temperatures and combined
310 with manure, substantially influenced the concentrations of key antinutrients: phytate, oxalate, saponin, tannin, and
311 cyanide, in jute mallow. As shown in Table 3, the most significant effects were observed in the combined biochar–
312 manure treatment at 450 °C (SBM450), which consistently produced the greatest reductions.

313 Saponin content decreased dramatically from 73.3 mg/g in the control soil to 14.2 mg/g under the SBM450
314 treatment, representing an 81% reduction. A similar trend was observed for phytate, which declined from 33 mg/g to
315 5.8 mg/g (82.4% reduction) under the same treatment for SBM450. These notable decreases suggest that ECNS
316 biochar, particularly when co-applied with manure and produced at moderate pyrolysis temperatures, may effectively
317 reduce antinutrient accumulation. This effect is likely mediated by enhanced adsorption of these compounds onto
318 biochar surfaces, increased microbial degradation stimulated by manure addition, or alterations in soil chemistry that
319 influence plant synthesis and uptake of antinutrients.

320 In contrast, reductions in oxalate, tannin, and cyanide levels were comparatively modest across all treatments. This
321 limited response indicates that the susceptibility of antinutrients to mitigation may differ based on their chemical
322 nature, metabolic pathway in the plant, and their interaction with biochar's physicochemical characteristics.

323 Overall, the results highlight the potential of ECNS biochar–manure amendments, particularly at 450 °C, to
324 improve the nutritional quality of jute mallow by significantly lowering key antinutritional factors. This demonstrates
325 an added value of biochar beyond soil improvement, reinforcing its role as a multifunctional amendment in sustainable
326 crop production.

327 Collectively, these findings indicate that ECNS-derived biochar not only enhances soil nutrient retention but
328 also modulates nutrient uptake profiles in jute mallow. This dual effect suggests that biochar application can
329 simultaneously improve crop nutritional quality and contribute to more sustainable soil management. The
330 selective enhancement of beneficial minerals such as K, Ca, and Zn, accompanied by moderated uptake of Fe
331 and Mn, aligns with previous studies that report biochar's capacity to regulate mineral bioavailability through
332 sorption, pH modification, and improved soil structure^{23,62}.

333

334 **2.6. Mechanism of Interaction of ECNS-Biochar with Manure in Soil Amendment**

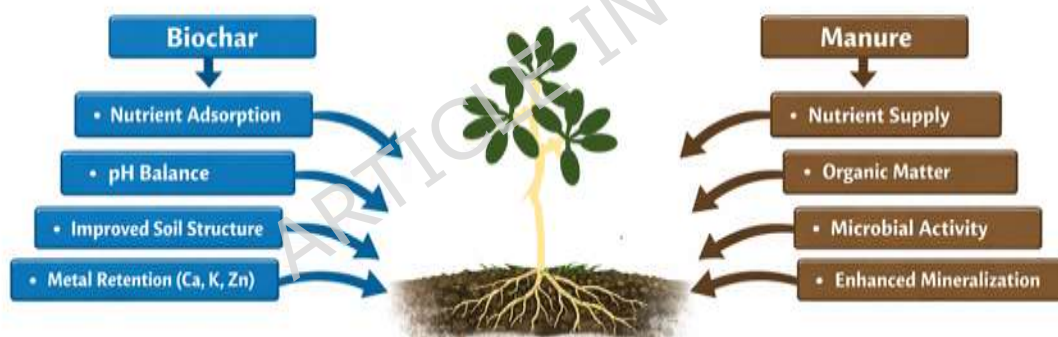
335 Mechanistically, the synergistic pathways through which ECNS-derived biochar and manure collectively enhanced
336 soil quality and jute mallow performance in this study are illustrated in Figure 4. Biochar primarily contributed through
337 its physicochemical properties, including high surface area, porosity, and CEC, which promoted nutrient adsorption
338 and retention. The observed increases in soil Ca, K, and Zn, as well as improved nutrient uptake by the crop, are
339 consistent with biochar's ability to stabilize nutrients in the rhizosphere and reduce leaching losses. Additionally, the

340 slight increase in soil pH toward a neutral–alkaline range likely improved nutrient availability and root activity, thereby
 341 supporting enhanced vegetative growth.

342 Manure, in contrast, served as an immediate source of readily available nutrients and organic matter, stimulating
 343 microbial activity and accelerating nutrient mineralization. This biological stimulation complements biochar’s largely
 344 physical and chemical functions. When co-applied, biochar acts as a nutrient reservoir, adsorbing nutrients released
 345 from manure and gradually making them available to plants. This interaction explains the superior agronomic
 346 performance observed under combined biochar–manure treatments, particularly at moderate pyrolysis temperatures.
 347 The downstream effects of this synergy were reflected in increased shoot and leaf development, improved nutrient
 348 composition of harvested jute mallow, and significant reductions in antinutritional factors such as phytate and saponin.
 349 The reduced antinutrient levels may result from altered soil chemistry, enhanced microbial degradation, and modified
 350 plant metabolic responses induced by improved nutrient status.

351 Generally, the complementary roles of biochar and manure integrate to improve soil structure, nutrient dynamics, and
 352 plant physiological performance are clear. These mechanisms collectively underpin the enhanced growth, nutritional
 353 quality, and sustainability outcomes demonstrated in this study, reinforcing the value of ECNS biochar–manure co-
 354 application as an effective soil amendment strategy.

355



356

357 *Figure 4. Mechanistic interaction of ECNS biochar with poultry manure for improved jute mallow yield and soil*
 358 *quality*

359

360 2.7 Statistical Analysis

361 The statistical analysis of the physical parameters revealed significant differences among leaf length, leaf breadth, and
 362 the number of leaves in jute mallow. The observed variation ($F(3, 8) = 15.320, p = 0.01, \eta^2 = 0.8517$) suggests that
 363 biochar and manure amendments differentially influenced vegetative growth traits. The high effect size ($\eta^2 > 0.8$)
 364 indicates a strong association between treatment type and plant morphological performance. Post-hoc comparisons
 365 showed that the number of leaves differed substantially from both leaf length and breadth, implying that leaf
 366 proliferation was more responsive to soil amendment than other growth parameters. This aligns with previous findings
 367 that biochar enhances leaf development by improving nutrient availability, root aeration, and microbial activity, which
 368 collectively support higher photosynthetic efficiency and canopy expansion.⁶³

369 In contrast, the absence of a statistically significant difference among soil treatments ($F(2, 9) = 1.116, p = 0.369$)
370 suggests that short-term application of ECNS biochar and manure did not markedly alter bulk soil properties within
371 the experimental timeframe. This may be attributed to the gradual nature of biochar's physicochemical interactions in
372 soil. Biochar's effects on cation exchange capacity, nutrient release, and microbial colonization often manifest over
373 longer periods, as reported in prior studies on soil-biochar dynamics. Therefore, while biochar improves plant
374 performance, its influence on overall soil characteristics may require longer cultivation cycles to become statistically
375 significant.

376
377 Regarding the mineral composition, the analysis revealed substantial differences among the elemental contents
378 ($F(6, 14) = 226.182, p = 0.001, \eta^2 = 0.989$), indicating that ECNS biochar significantly affected nutrient
379 accumulation in jute mallow. The elevated mean values of calcium (Ca), potassium (K), and magnesium (Mg)
380 relative to other elements suggest enhanced nutrient uptake efficiency for these macronutrients. This
381 improvement could be attributed to biochar's high surface area and cation exchange capacity, which facilitate
382 nutrient adsorption and retention in the rhizosphere, making these elements more bioavailable to plants.

383 The finding that Ca, K, and Mg concentrations were significantly higher than those of Fe, Mn, Pb, and Zn reflects
384 the selective adsorption behaviour of ECNS biochar. The reduced accumulation of heavy metals such as Pb and
385 Mn further underscores biochar's potential in minimizing metal toxicity through immobilization mechanisms.
386 This agrees with literature reports that biochar can simultaneously enhance essential nutrient uptake while
387 mitigating heavy metal bioavailability in crop systems.

388 Overall, these results demonstrate that while biochar and manure may not cause immediate large-scale changes
389 in soil physicochemical parameters, they exert profound effects on plant growth and nutrient dynamics. The
390 significant differences observed in growth parameters and mineral uptake confirm the beneficial role of ECNS-
391 derived biochar as a sustainable soil amendment that promotes nutrient efficiency and plant productivity in jute
392 mallow cultivation.

393

3 Materials and Methods

3.1 Description of Pyrolysis Reactor

A fluidized bed fast pyrolyzer was specially fabricated and used for this study. The reactor was made of galvanized aluminum containing a beam chamber where insulative blocks were used as inner lining. The insulative material is made of refractory powder clay mixed with wood dust and baked in block-shapes at 1500 °C to burn off the wood particles. The blocks preserve the heat in the inner chamber in a muffle form. The heating spring element is made of titanium base and can heat uniformly to 1200 °C maximum. This was coiled uniformly round in the inner part of the refractory lining which serves as the only source of heat generated electrically using alternating current of 220-240 V. The inner chamber serves as the container for the charge. It is positioned just in front of the heating element to be heated by radiation. The base of the inner chamber has baffle plates through which nitrogen can fluidize the pyrolyzed feedstock. Connected to the chamber are two cyclones in series to separate the solid product (biochar) from other volatile product. The cyclones are then connected to a long cooling jacket for collecting liquid product. A thermocouple sensor is also connected to the reactor which picks the heating state and forward it through the probe that leads outside the heating chamber to connect the temperature controller. The temperature controller interprets the sensed temperature in degrees. It is also used in regulating and controlling the inner temperature of the inner chamber. Its operation face is visible outside the pyrolyzer. Full schematic diagram of the reactor is presented in supplementary information (Section 1).

3.2 Pyrolysis of ECNS

600 g ECNS, collected from our previously reported study ⁴, was weighed, ground, and fed into the pyrolyzer. Temperature was set to 450 °C, ramped at 100 °C min⁻¹ and held for 1 hr and inert gas (nitrogen) was made to flow at 100 ml min⁻¹. The solid product (biochar) was collected, weighed and kept. The process was repeated with the same amount of ECNS at 550 °C and 650 °C respectively. Yield of volatiles were determined according to equation 1

$$A - B = C \quad (1)$$

Where A = mass of ECNS charged into the chamber, B = mass of biochar recovered and C = mass of volatiles evolved.

3.3 Characterisation of ECNS Biochar

Elemental analysis for the biochar was done on a LECO CHNS instrument. Sample, 2-5 mg, was weighed and placed into the autoloader of the instrument and was automatically dropped into the high-temperature combustion furnace, allowing the sample to combust. This combustion converted carbon to carbon dioxide, hydrogen to water, nitrogen to nitrogen gas, and sulphur to sulphur dioxide. The gases were swept from the furnace and detected by independent detectors.

Higher heating value (HHV) of the biochar sample was determined by calorimetry using an e2K calorimeter by burning a known weight of biochar in the bomb of the calorimeter with oxygen level regulated to 3 kPa ⁶.

429 3.4 Cultivation of Jute Mallow using Biochar as a Soil Amender

430 Pot experiments were conducted by planting jute mallow using a polythene bag half-filled with 7 kg sandy soil, to
 431 which 7 g biochar at different temperatures i.e. 450 °C, 550 °C and 650 °C was added. Poultry droppings were obtained
 432 from the agricultural farm of Lagos State University of Education Lagos, Nigeria. 21 g poultry droppings and 7 g
 433 biochar were added when co-applied to the soil. Composition of pot experiment is as presented in Table 4. The set-up
 434 was monitored and watered during the period of germinations. All the pot experiments were done in triplicate.

435

436 *Table 4. Composition of pot experiments with biochar from ECSN as soil amenders in the cultivation of jute mallow*

Entry	Composition				Remark
	Soil	Biochar	Biochar Temperature	Manure	
1	+	-	-	-	Soil + Plant
2	+	+	450 °C	-	SB450
3	+	+	550 °C	-	SB550
4	+	+	650 °C	-	SB650
5	+	+	450 °C	+	SBM450
6	+	+	550 °C	+	SBM550
7	+	+	650 °C	+	SBM650

437

438 3.5 Agronomic Parameters Measurement

439 Agronomic measurements were conducted to assess the growth response of jute mallow under the various soil
 440 amendment treatments. Physical growth parameters, including shoot length, root length, leaf length, leaf breadth, and
 441 leaf number, were recorded at two key developmental stages: 4 weeks and 8 weeks after planting.

442 For each plant, shoot and root lengths were measured using a standard measuring tape from the base of the stem
 443 to the shoot apex and root tip, respectively. Leaf length and breadth were determined using a digital calliper or ruler,
 444 with length measured from the petiole junction to the leaf tip, and breadth measured across the widest section of the
 445 leaf blade. Leaf number was quantified by manually counting all fully expanded leaves per plant.

446 All measurements were taken carefully and consistently across replicates to ensure accuracy and minimize
 447 observational bias. The collected data were then compiled and statistically analysed to determine significant
 448 differences among treatments and to evaluate the overall effect of ECNS biochar and manure on plant growth.

449

450 3.6 Effect of Biochar on Quality of Plant and Soil

451 **3.6.1 Proximate Analysis** Cultivated plant and soil were subjected to proximate (moisture contents, ash contents,
 452 volatile matter contents, and fixed carbon contents) and physiochemical analyses. Moisture (M) contents, ash (A)
 453 contents, and volatile matter (VM) contents were experimentally determined following standard methods as stated in

454 the supplementary information section 2, while fixed carbon (FC) contents were calculated by difference, that is,
455 $FC=100-VM-M-A$.

456 **3.6.2 Mineral Analysis** Soil samples were digested using Kjeldahl flask with the aqua mixture and analyzed using
457 atomic absorption spectrophotometer (AAS) in appropriate instrumental conditions while flame photometer was used
458 to analyze potassium. Phosphorous determination was done using a UV-visible spectrophotometer. Full description
459 of the soil digestion for metal and phosphorous determination is in the section 3 of the supplementary information.

460 **3.6.3 Anti-Nutritional Analysis** Anti-nutritional properties of the harvested were determined. Tannin, saponin,
461 oxalate, phytate and total cyanide were determined following standard methods as fully described in the supplementary
462 information section 4^{64,65}.

463 **3.7 Statistical Analysis**

464 A statistical analysis was performed using a one-way between-groups analysis of variance to explore the impact of the
465 physical parameters. Equally a post-hoc comparisons using the Tukey HSD Test was conducted at a significance level
466 of $p = 0.05$ while an independent –sample t-test was conducted to compare the readings.

467

468 **Conclusions**

469 The study explored the valorisation of extracted cashew nut shell (ECNS) waste through pyrolysis to produce
470 biochar for use as a soil amendment in jute mallow cultivation. Biochars were generated at varying pyrolysis
471 temperatures (450–650 °C) and applied to soil alone and in combination with poultry manure.

472 Application of ECNS biochar markedly improved soil fertility, crop growth, and nutritional quality. Biochar
473 treatments significantly enhanced shoot and leaf growth parameters, with the 550 °C biochar (SB550) showing the
474 highest agronomic performance. Co-application with manure (SBM550) further amplified these effects, indicating
475 synergistic nutrient enrichment and improved soil structure. Soil analyses revealed substantial increases in
476 phosphorus, nitrate, organic matter, and nitrogen contents, while pH shifted slightly toward the optimal alkaline range
477 (7.0–7.4).

478 Nutritionally, the harvested jute mallow exhibited increased protein, fat, and crude fibre contents, accompanied
479 by reductions in carbohydrate and ash levels. Biochar and manure amendments also enhanced soil and plant uptake
480 of essential minerals such as Ca, K, Mg, and Zn, while reducing the presence of antinutritional factors (notably phytate
481 and saponin)—most effectively with SBM450.

482 Overall, the study demonstrates that ECNS-derived biochar, particularly when combined with organic manure,
483 serves as an effective and sustainable soil amendment. It enhances soil physicochemical properties, supports vigorous
484 jute mallow growth, improves crop nutritional quality, and reduces antinutrient accumulation, highlighting its potential
485 role in sustainable agriculture and waste valorisation.

486

487

488

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643 **Declarations**

644 **Data Availability:** Dataset used in the study will be provided upon reasonable request directed to the
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650 Conceptualization, JKO; design and fabrication, JKO; methodology, JKO, MOA and LL; investigation, MOA,
651 OEO; data curation, MOA, JKO; formal data analysis, MOA, JKO; writing—original draft preparation, MOA,

652 JKO; writing—review and editing, JKO, LL; visualization, JKO; funding, JKO, MOA; supervision, JKO,
653 OOO and LL.

654 **Conflict of Interest:** Authors declare no conflict of interest.

655 **Ethics approval:** Not applicable

656 **Figure Legends**

657
658 *Figure 1. Primary valorization of cashew nut shell to liquid chemicals and a further secondary valorization of*
659 *the extracted shell to biochar which was subsequently applied as soil amender in the cultivation of jute mallow.*

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661 *Figure 2. ECNS Pyrolysis product distribution as biochar and volatile at different conditions of temperatures*

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663 *Figure 3 Effect of biochar and manure addition on the mineral content of the soil (top) and in the plant (bottom)*
664 *after harvesting.*

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666 *Figure 4. Mechanistic interaction of ECNS biochar with poultry manure for improved jute mallow yield and soil*
667 *quality*

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688 *Table 1. Proximate Analysis of ECNS-based Biochar at Different Temperatures*

Pyrolysis Temperature	Moisture Content (%)	Volatile Matter Content (%)	Ash Content (%)	Fixed Carbon Content (%)
ECNS	1.10 ± 0.05	8.41 ± 0.07	3.1 ± 0.00	87.39
450 °C	0.37 ± 0.05	4.09 ± 0.18	5.68 ± 0.65	89.86
550 °C	0.12 ± 0.03	2.14 ± 0.18	7.63 ± 0.57	90.11
650 °C	0.08 ± 0.02	1.25 ± 0.11	9.26 ± 0.33	89.41

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715 *Table 2 Elemental Analysis and Energy Values of ECNS Biochar at Different Temperatures*

Pyrolysis Temperature	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Sulphur (%)	HHV (MJkg⁻¹)
450 °C	41.80± 0.3	8.34 ± 0.2	0.40 ± 0.1	48.55± 0.6	0.15 ± 0.1	38.30
550 °C	43.82± 0.1	8.25 ± 0.3	0.39 ± 0.1	46.68± 0.2	0.12 ± 0.1	33.60
650 °C	44.29± 0.5	8.01 ± 0.3	2.37 ± 0.1	44.13± 0.2	1.20 ± 0.0	40.30

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745 *Table 3 Agronomic, physicochemical, proximate and anti-nutritional analyses of soil, biochar and harvested jute*
 746 *mallow. Agronomic data were mean values of jute mallow at 4 weeks and 8 weeks.*
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Parameter	Soil alone	Soil + plant alone	SB450	SB550	SB650	SBM450	SBM550	SBM650
<u>Agronomic Analysis</u>								
Shoot length (cm)	46.8±4.8	-	60.7±8.3	75±13.3	61.6±10.3	87.4±11.6	81.7±12.1	83.0±9.9
Leaf length (cm)	5.8±1.1	-	8.5±0.4	9.0±0.5	9.2±1.9	9.1±4.6	9.0±3.7	9.8±2.2
Leaf breadth (cm)	2.5±0.5	-	4.0±0.4	5.5±0.3	3.8±0.0	6.4±0.9	5.6±0.2	5.4±0.9
Root length (cm)	10.0±1.9	-	10.6±0.8	10.8±2.5	14.6±10.8	12.2±0.8	11.6±0.2	22.5±16.2
Leaf number	12.7±2.8	-	13.1±0.0	18.7±5.1	14.4±3.2	33.1±14.5	29.9±11.1	41±10.8
<u>Physicochemical analysis</u>								
pH	6.8±0.1	7.4±0.0	7.4±0.1	7.3±0.1	7.5±0.1	7.3±0.1	7.2±0.1	7.3±0.0
Organic Matter (g/kg)	8.4±0.2	11.3±0.2	17.2±0.2	19.4±0.2	16.0±0.2	22.2±0.2	28.1±0.6	22.5±0.2
Phosphorus (g/kg)	50.2±0.2	70.8±0.2	108.0±0.2	143.0±0.4	126.0±0.4	153.9±0.3	224.8±0.3	176.1±0.4
Nitrogen (g/kg)	0.2±0.0	0.3±0.0	0.5±0.0	0.6±0.2	0.3±0.2	0.7±0.0	0.9±0.2	0.7±0.0
Nitrate (g/kg)	51.2±0.2	63.2±0.3	82.2±0.2	85.5±0.2	60.8±0.2	88.5±0.0	113.6±0.2	97.0±0.5
CEC (c/mol/g)	9.1±0.0	8.4±0.2	8.5±0.2	8.6±0.0	8.6±0.0	7.9±0.1	8.6±0.1	7.5±0.1
<u>Proximate analysis</u>								
Moisture (%)	-	12.2±0.0	11.7±0.1	11.8±0.0	12.8±0.1	12.4±0.2	12.1±0.0	12.0±0.1
Ash (%)	-	10.3±0.1	9.7±0.1	9.3±0.2	9.7±0.3	10.5±0.1	9.5±0.1	9.8±0.1
Protein (%)	-	13.6±0.2	15.8±0.1	16.2±0.0	17.5±0.3	20.6±0.5	22.9±0.5	19.0±0.2
Crude Fibre (%)	-	12.6±0.1	13.4±0.14	14.4±0.1	12.2±0.0	13.5±0.1	14.1±0.1	13.9±0.0
Fat (%)	-	12.8±0.1	14.2±0.0	15.6±0.1	14.6±0.1	15.3±0.0	18.3±0.1	16.3±0.1
Carbohydrate (%)	-	39.0±0.3	35.3±0.0	32.5±0.3	32.6±0.2	27.6±0.5	23.1±0.4	30.0±0.2
<u>Anti-nutritional content</u>								
Phytate (mg/g)	-	33.0±0.1	14.8±0.3	17.3±0.5	15.7±1.1	5.8±0.1	8.2±0.2	8.2±0.1
Oxalate (mg/g)	-	3.8±0.8	2.3±0.0	3.2±0.0	2.8±0.1	1.2±0.0	1.9±0.0	1.7±0.0
Saponin (mg/g)	-	73.3±1.2	27.3±0.5	40.2±0.8	28.9±0.9	14.2±0.2	21.8±0.3	21.8±0.3
Tanin (mg/g)	-	2.9±0.0	2.7±0.1	2.9±0.1	2.9±0.0	2.4±0.0	2.7±0.1	2.6±0.0

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Cyanide (mg/g)	-	0.9±0.0	1.9±0.0	0.7±0.0	0.9±0.0	1.6±0.1	0.3±0.0	2.3±0.1
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