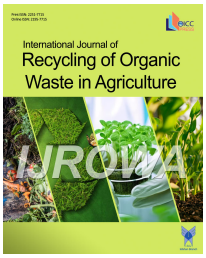


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# Crosslinker effect on composite synthesis of alginate with activated carbon and nanocellulose as micronutrient slow-release fertilizer

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**Original Research**

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**Abstract:**

**Purpose**: Oil Palm Empty Fruit Bunches (OPEFB) solid waste has potential as a feedstock to be transformed into nanocellulose and activated carbon. In this study, we observed the effect of various compositions of activated carbon, alginate, and nanocellulose on the production of micronutrient slow-release fertilizer composites.

**Method**: The composite of activated carbon/alginate/nanocellulose (C/Alg/NC) with various compositions of 1:1:1; 3:1:1; 1:3:1 and 1:1:3 was synthesized and characterized by using FTIR, XRD, and SEM-EDX analysis. Crosslinked effects by Cu and Fe were observed, and composite C/Alg/NC showed slower release of Cu ions, which indicates a good strategy to produce micronutrient slow-release fertilizer.

**Results**: The best composite as a slow-release fertilizer for Cu metal is a 3:1:1 ratio. Over two days, it released 0.05 mg/g, and on the third day, it released an increase up to 0.27 mg/g after five days. Meanwhile, the Fe crosslinker composite with the same composition ratio (1:1:1) performed best as a slow-release fertilizer because Fe released slowly at only around 0.05 mg/g for up to three days. Then, for the next three days, until the $6^{th}$ day, Fe was released slightly more, up to 0.3 mg/g, and then remained constant until the $9^{th}$ day.

**Conclusion**: The synthesis of composites from a combination of carbon, alginate, and nanocellulose has become a good strategy for producing slow-release fertilizer. It has also become a solution for utilizing OPEFB solid waste, while this slow-release fertilizer can be used as a source of plant nutrition in oil palm plantations.

**Keywords:** Compost; Cross linker synthesis; Oil palm empty fruit bunches; Plant nutrition

## 1. Introduction

Oil Palm Empty Fruit Bunches (OPEFB) is the most abundant solid waste generated from fresh fruit bunches (FFB) palm oil processing, and it is becoming one of the contributors to environmental pollution. The products generated from palm oil processing, including OPEFB are 0.20 – 0.23 ton/ton FFB; mesocarp fiber of 0.12 – 0.13 ton/ton FFB; palm kernel shell of 0.05 – 0.06 ton/ton FFB; boiler ash 0.005 – 0.006 ton/ton FFB; and POME (palm oil mill effluent) of 0.77–0.84 $m^3$/ton FFB. OPEFB is green, abundant, and rich in carbon content and has undergone extensive processing to be transformed into adsorbents, specifically in the form of activated carbon (Hasanudin et al., 2015; Muchtar et al., 2023; Thoe et al., 2019). On the other hand, OPEFB is rich in cellulose, hemicellulose, and lignin at 40–50%, 20–30%, and 20–30%, respectively. This also has a high potential to convert OPEFB solid waste into nanocellulose

(Lubis et al., 2020; Prastiwi et al., 2019; Sari et al., 2021). In our previous report, we successfully synthesized an activated carbon/alginate-Fe composite derived from activated carbon from OPEFB and analyzed it as a material for slow-release fertilizer. The kinetic study showed that after composites were contacted with citric acid, the concentration of Fe was directly dropped, becoming stagnant, and/or releasing gradually from 60 minutes to 3 days (Septevani et al., 2020; Zubir et al., 2021). This study was also confirmed by Prastiwi et al. (2019), who analyzed Cu, Fe, and Zn impregnated activated carbon as slow-release fertilizer. They suggested that the nutrient release rate depends on the diameter of the trace metal; for example, among the three elements, zinc showed the ease of release from activated carbon (Lani et al., 2014; Wu et al., 2023). Furthermore, the properties of activated carbon, including specific surface area and pore volume, also influenced the micronutrient loading as well as the release mechanism. The strong interaction between elements and activated carbon structures also affected the leaching mechanism of nutrients (Djangkung et al., 2020; Harahap et al., 2014; Priyadi and Mangiring, 2019).

In general, most conventional micronutrient fertilizers commonly used worldwide today are water-soluble salts, like sulfates, or their chelated forms, such as EDTA and DTPA. The water solubility of these materials leads to the processes of leaching and run-off, as well as nitrogen fixation by soil (Kassem et al., 2022b). Furthermore, they demand high dosages and have unfavorable cost-economics. In addition, nutrient leaching contributes to environmental pollution by causing soil damage and contaminating groundwater through nutrient accumulation at a particular location. Consequently, certain regions will experience a deficiency of micronutrients in plants, while in other regions, plants will be harmed by the excessive buildup of micronutrients. Therefore, developing slow-release fertilizer is one of the solutions to this problem. By trapping trace metal trapped inside activated carbon, the nutrient could not easily leach out while contacting water (Han et al., 2008; Kassem et al., 2022a).

To enhance the amount of micronutrient loading and to create a slow-release fertilizer that can release micronutrients over a longer period of time, polymers are widely used as coating materials. In the present studies, it is crucial to select environmentally friendly, biodegradable, and sustainable polymers for coating materials to prevent further environmental pollution. Cellulose is a natural polymer derived from biomass and widely used as a coating agent for slow-release fertilizer. Kassem et al. (2022a) designed a biobased cellulose coating material for monoammonium phosphate fertilizer (MAP), with the maximum release longevity being 12 hours in water and 19–20 days in soil. Further research showed that they combined cellulose with biochar, becoming biobased cellulose/biochar and successfully reduce phosphor (P) leaching by 43.90% during 80 days of soil incubation (Sutirman et al., 2021; Rana et al., 2024). Therefore, it has potential as a feedstock to obtain polymer cellulose and utilize it as a coating agent for developing micronutrient slow-release fertilizer composites. Also, alginate is a natural polymer derived from alginic acid and widely used as an encapsulated matrix in the applications of biomedical engineering, the food and cosmetic industries, and slow-release fertilizer. In biomedical engineering applications, the purpose of encapsulating is to protect bioactive molecules from temperature, moisture, and acidic conditions. The properties of cellulose and alginate are easily modified with a number of additives (Chai et al., 2021; Gao et al., 2020).

In this research, activated carbon and nanocellulose were obtained from OPEFB, and the modified product was combined with alginate and trace metal ions as a hydrogel composite via a crosslinking mechanism. This work offers an optimization of low-cost and abundant OPEFB waste into value-added materials and applying it as an environmentally friendly slow-release fertilizer.

## 2. Materials and methods

### Activated carbon preparation

Activated carbon derived from OPEFBs was prepared from our previous work (Septevani et al., 2020). At initial, OPEFB solids were washed, dried, and grilled into OPEFB powder. OPEFB powder samples were heated at 500 °C for 2 minutes. Samples were cooled to room temperature and kept in a dry vessel. Carbon was then soaked in a 10% $H_3PO_4$ solution for 24 hours to form OPEFB-activated carbon. The activated carbon formed was filtered and washed with distilled water until it reached a neutral pH, then continued to dry at 105 °C.

### Nanocellulose isolation

Nanocellulose was synthesized by following a previous work (Sari et al., 2021). OPEFBs were cut and grinded into fibers shapes and boiled for 2 hours at 70–80 °C in a flask containing 0.7% sodium chlorite ($NaClO_2$) solution, which was acidified using acetic acid until pH = 4, and the fibers and $NaClO_2$ solution ratio was 1:50. This bleaching process was repeated four or five times until the fibers turned a white color. The white residue was washed with distilled water and dried in open air, then heated at 70–80 °C for 2 hours in a flask containing 5% (w/v) sodium sulphite solution, then filtered, washed, and dried. The dried fibers were treated with an alkaline solution of 17.5% (w/v) NaOH for 2 hours, then washed several times and dried at room temperature. The obtained cellulose was hydrolyzed for 45 minutes at 45 °C in a 64% wt sulfuric acid solution with strong agitation. The cold water was added to the hydrolysis solution to stop the reaction. The diluted sample was centrifuged for 10 minutes in order to obtain a precipitate. Dialysis was performed for three days after this procedure was repeated until the pH of the suspension reached 5.

### Activated carbon/alginate/nanocellulose (C/Alg/NC) composite synthesis

A series of samples with different ratios of activated carbon, sodium alginate, and nanocellulose were prepared according to the following method: Activated carbon, sodium alginate, and nanocellulose were dissolved in 100 mL of distilled water and stirred until homogeneous. The mixture solution was dripped slowly into 0.1 M $FeCl_3$ to form

hydrogel beads composites and left for 24 hours until the crosslinking process was complete. The composites were washed with distilled water until they reached a neutral pH and then dried in an oven. The ratios of activated carbon (AC), alginate (Alg), and nanocellulose (NC) were 1:1:1, 3:1:1, 1:3:1, and 1:1:3. The same procedure was used to prepare the composite with Cu from the $CuSO_4$ solution. The illustration of the activated carbon/alginate/nanocellulose composite preparation is described in Fig. 1.

### Composite characterization

Activated carbon, nanocellulose, alginate, and all composite samples were characterized by Fourier transform infrared (FTIR) for functional group analysis, X-ray diffraction (XRD) to determine structural change, and scanning electron microscopy-energy dispersive X-ray (SEM-EDX) to observe the morphology change of each composite.

### Test of the release of Fe and Cu from AC/Alg/NC composites in the citric acid media

0.5 g of composite sample was immersed in 50 mL of 0.33 M citric acid solution with a variety of times (2, 3, 4, 5 days). Then, filtrate containing $Fe^{3+}$ or $Cu^{2+}$ was analyzed using atomic absorption spectroscopy (AAS).

## 3. Results and discussion

### Synthesis of activated carbon/alginate/nanocellulose crosslinking Cu and Fe

Differences in amount between activated carbon, alginate, and nanocellulose used in composites influence the solution texture, shape, and strength of the composite. These variations also affect the interactions that occur, which could include hydrogen bonds between activated carbon and nanocellulose, activated carbon and alginate, and interactions between alginate and nanocellulose. Hydrogen bonds can arise between nanocellulose and alginate. The interesting thing is that when Cu and Fe metals were added, they reacted with alginate to produce an egg-box interaction of cation and alginate, which was indicated by the formation of beads (White and Brown, 2010; Wu et al., 2023; Xie et al., 2018).

Using alginate in larger quantities resulted in a very thick composite solution texture, which arose from the gel properties of the alginate, and a composite with a more rounded, sturdy, and dense bead shape were obtained. When washed, the bead shape did not crumble. When activated carbon was used in larger quantities, it produced a dark black liquid solution texture, resulting in a composite with a less round, firm, and dense bead shape. The excess composites had a liquid solution texture, a bead shape that was round, slightly firm, and dense was obtained, which was slightly destroyed during washing. Similarly, when more nanocellulose was used, the resulting composite had a liquid solution texture and a bead shape that was round, slightly firm, and dense. These characteristics did not crumble when it was washed.

### FTIR characterization analysis

FTIR analysis of alginate, nanocellulose, and various ratios of C/Alg/NC composite were measured, and the hydroxyl (-OH) group is shown by the broadband at around $\sim$ 3200 to 3400 $cm^{-1}$ for all materials (Fig. 2 (a)). Alginate's FTIR spectra reveal absorption in the following areas: 3244 $cm^{-1}$, which indicates the existence of a hydroxyl group; 1584 $cm^{-1}$, which indicates carbonyl; 1412 $cm^{-1}$, which indicates the presence of C-O-H bonds; and 1052 $cm^{-1}$, which indicates the presence of C-O-C and –COOH bonds.

Moreover, in the FTIR spectrum of nanocellulose, there are absorptions at wavenumbers 3442 $cm^{-1}$ and 2898 $cm^{-1}$, indicating stretching vibrations of OH groups and stretching of C-H bonds in the cellulose chain. Absorption at wavenumbers 1641 $cm^{-1}$ indicates water absorption by cellulose molecules caused by the reaction between NaOH with cellulose hydroxyl groups and the subsequent formation of water molecules. The water absorbed by the cellulose molecules was very difficult to extract, even though

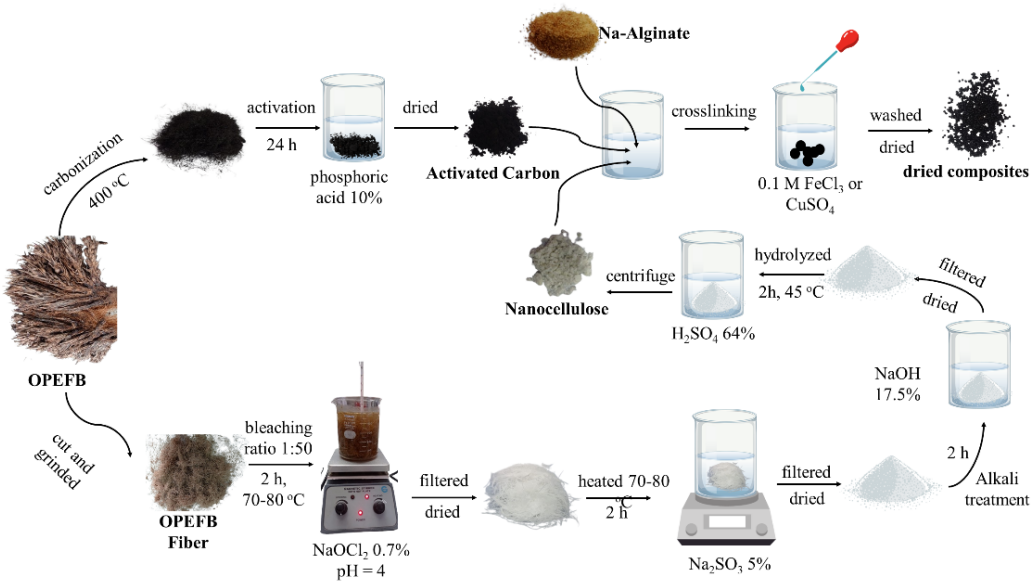


**Figure 1.** The CS sample chemical composition.

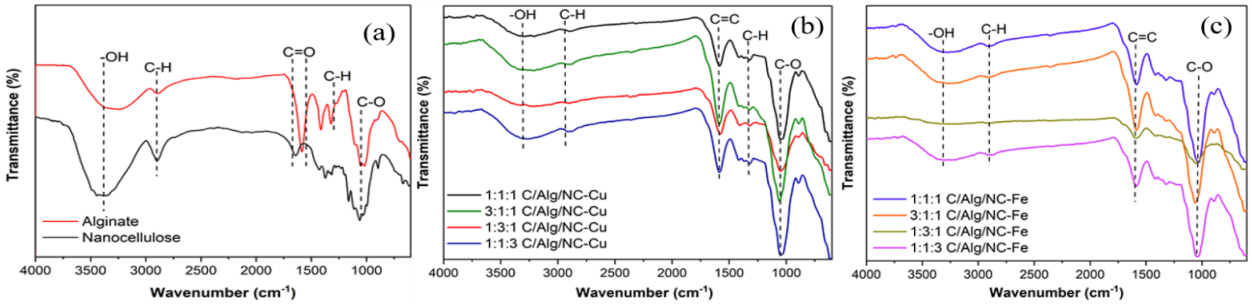


**Figure 2.** FTIR spectra of cellulose, lignin and hemicelluloses isolated from CS.

the processed fiber had undergone a drying process. This occurred because of the interaction between cellulose and water.

The bending vibration of the C-H and C-O bonds in the aromatic polysaccharide ring is indicated by a wavenumber of approximately 1300 $cm^{-1}$. The presence of C-O stretching absorption is indicated by a wavenumber of 1161 $cm^{-1}$. The C-O-C glycosidic bond vibration (stretching of the pyranose ring) is indicated by a wavenumber of 1060 $cm^{-1}$. The glycosidic deformation of -C1-H is represented by the absorption at wavenumber 895 $cm^{-1}$, with contributions from ring vibration and -O-H bending. The characterization of the $\beta$-glycosidic bonds between cellulose's an-hydro glucose units as one of these properties (Leppiniemi et al., 2017; Siqueira et al., 2019).

The functional groups of all FTIR C/Alg/NC composites (Fig. 3 (b) and 3 (c)) are comparable to those of the individual. The hydroxyl group of C/Alg/NC shifted slightly to the lower wavenumber, indicating a stronger hydrogen bond within the composite with the addition of constituent materials. The C-H asymmetric stretching from the alkyl group is observed at 1320 $cm^{-1}$ and 2915 $cm^{-1}$. Other peaks are observed at 1637 $cm^{-1}$, 1593 $cm^{-1}$ and 1058 $cm^{-1}$ associated with C=O stretching vibration, C=C stretching vibration and C-O group, respectively. In addition, the peak shift from raw materials in all variations C/Alg/NC is due to the influence of Cu and Fe cross-linking. The formation of ionic bonds between the cations and the carboxylate groups of the modified composites are affected the peak to shift toward a lower wavenumber. Moreover, these bands confirm the success of C/Alg/NC synthesized.

Interestingly, when the C/Alg/NC ratio is the same (1:1:1), it shows a similar intensity to when the composition ratio is 1:1:3 for both Cu and Fe metals. This shows that a larger amount of nanocellulose does not affect changes in the reactions of the existing functional groups. Meanwhile, the ratio of the greater amount of active carbon and alginate, although it shows no change in the presence of the functional groups formed, affects the intensity of the C=C and C-O bonds, which shows the formation of interactions with each other through addition and elimination reactions.

Using a Cu metal crosslinker (Fig. 2 (b)), the ratio of 3:1:1 C/Alg/NC increases the intensity of the C=C group, indicating that increasing the amount of active carbon increases the number of reactions between hydrogen groups on active carbon and -OH groups on nanocellulose and alginate. In the 1:3:1 C/Alg/NC composition, the intensity of the C-O group decreased, indicating that the excess alginate composition promotes the reactivity of -OH groups in alginate with -H groups in hydrocarbons and -H groups in nanocellulose, producing the formation of water molecules.

A similar effect occurs when Fe metal is used as a cross linker (Fig. 2 (c)), particularly for the 3:1:1 C/Alg/NC ratio, which results in an increase in C=C groups but with a lower intensity than when Cu is used. It suggests that the interaction of alginate and nanocellulose with Fe and Cu metals produces various effects. Because Fe is a trivalent metal and Cu is a divalent metal, their characteristics are different. Physically, Fe is more rigid, which impacts the pace of gel formation (Evelyna et al., 2019; Klinkajon and Supaphol, 2014; Massana Roquero et al., 2022).

The difference in characteristics between Cu and Fe metals is also reflected in the composition ratio of 1:3:1 C/Alg/NC, where with Cu metal, only the C-O group intensity decreases, whereas with Fe metal, both the C-O group and the C=C group decrease. The increase in the C=C group

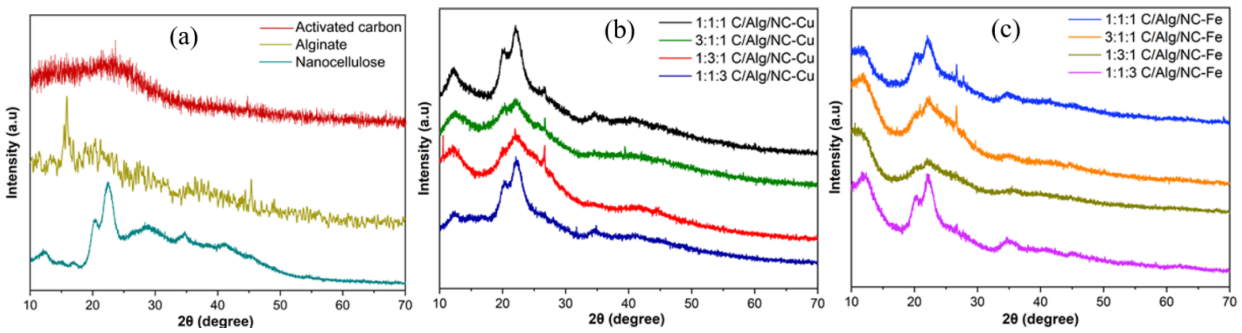


**Figure 3.** The biofertilizer pellets obtained.

is due to a strong connection between the iron atom and the OH groups in the alginate. This is because the alginate has an excessive composition of (1:3:1 C/Alg/NC), which has the most impact on the formation of the cation-alginate egg-box interaction.

### XRD characterization analysis

The XRD patterns (Fig. 3) of activated carbon at 2 of 23.16° are an indication of the amorphous state of activated carbon. Peaks appeared at 2 of 15.65° and belong to the alginate structure. Nanocellulose appeared at 2 of 22.3° corresponding to crystal plane of cellulose (200). All composite materials exhibit a dominant peak at $2\theta$ of 19° – 24°. The intensity of the peaks varies depending on the constituent materials. The broadening peak of C/Alg/NC-Cu and C/Alg/NC-Fe in a 1:3:1 ratio caused a higher alginate composition. The alginate structure might be distorted due to hydrogen bonding interactions between the hydroxyl (–OH) and carbonyl (C=O) groups of alginates and the hydroxyl groups of nanocellulose. The crystalline peak appeared on the C/Alg/NC-Cu and C/Alg/NC-Fe in a 1:1:3 ratio, which affected the addition of nanocellulose to the composition.

XRD patterns for 1:1:1 C/Alg/NC and 1:1:3 C/Alg/NC show different XRD patterns than the other two ratios for both Cu and Fe metals, which backs up the FTIR data. The decrease in absorption peaks of the C=C and C-OH groups in the FTIR spectrum of 1:3:1 C/Alg/NC with Fe is also supported by a decrease in crystallinity, as seen in the CRD patterns. In the same way, the appearance of a strong peak in the XRD data supports the idea that the O-H group's absorption goes up at 1:3:1 C/Alg/NC with Cu. It indicates that the creation of a cation-alginate egg-box interaction with Fe metal is more robust than with Cu metal, as illustrated in Fig. 4.

### SEM-EDX characterization

SEM images observed the differences in morphology in composite formation caused by different composition variations. SEM images of activated carbon, alginate, and nanocellulose demonstrate distinct morphologies (Fig. 5). The SEM morphology of activated carbon reveals that the exterior structure forms pore cavities of vast and even depths, while the surface is non-unalike and uneven in shape, indicating that the activated carbon is amorphous. Alginate has elongated particles that form aggregates. Meanwhile, nanocellulose has a flatter, smoother, and more fibrous fiber surface structure due to the removal of non-cellulose components.

The SEM image of the four composites for Cu and Fe crosslinkers exhibits morphological changes compared to the SEM image of the three raw materials that make them up, indicating that they have mixed and bonded each other and that Cu metal has been absorbed (Fig. 6). The SEM pictures of the 1:1:1 C/Alg/NC-Cu and 1:1:3 C/Alg/NC-Cu composites exhibit similar morphology to the FTIR and XRD analyses presented above. The addition of more nanocellulose to the 1:1:3 C/Alg/NC-Cu composite did not alter the interactions. Meanwhile, the 3:1:1 and 1:3:1 C/Alg/NC-Cu composites have distinct morphologies, indicating variations in the type of bond that occur, as described by FTIR and XRD data. Furthermore, the 3:1:1 C/Alg/NC-Cu composite showed more homogeneous particle formation compared to the other 3 Cu composites.

The similar phenomenon is also observed in the identical morphology of 1:1:1 C/Alg/NC-Fe and 1:1:3 C/Alg/NC-Fe (Fig. 7), indicating that increasing the nanocellulose amount just creates nanocellulose, which has a function as a template for this composite. Increasing the amount of alginate (1:3:1 C/Alg/NC-Fe) and active carbon (3:1:1 C/Alg/NC-Fe) produces variations in interactions during composite production, as previously indicated by FTIR data. Despite having distinct morphologies, these two compositions exhibit excellent uniformity.

An energy dispersive X-ray (EDX) analysis was carried out to identify the elemental composition of C/Alg/NC. The element peaks of C, O, Cu, and Fe were observed in all C/Alg/NC cross-linked composites. The crosslinking with Cu and Fe was successfully prepared in C/Alg/NC, as it obviously appeared in the analysis. Both ratios of 3:1:1 of

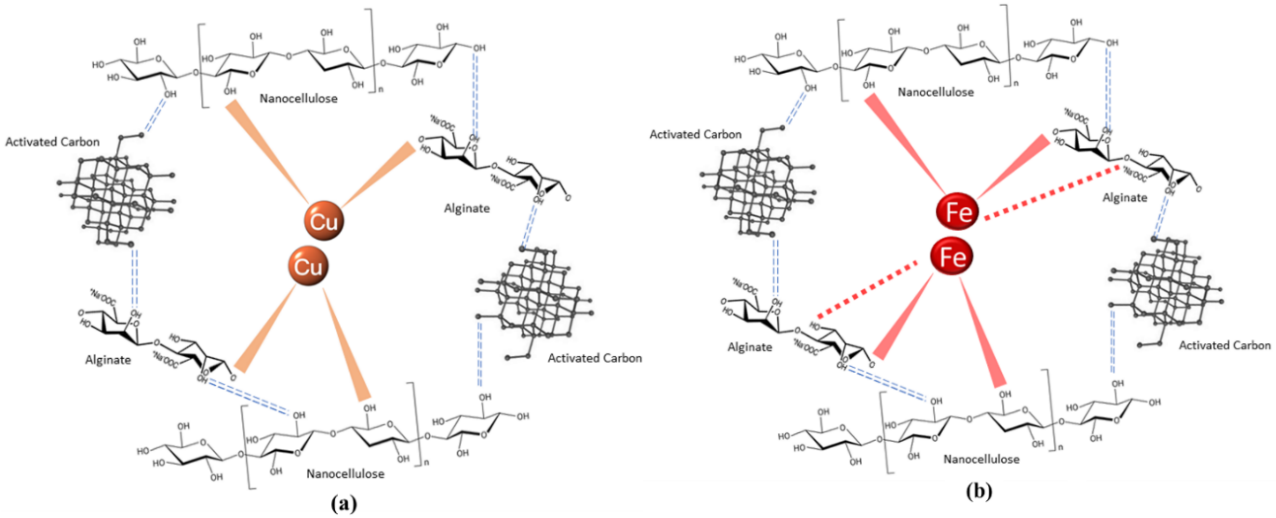


**Figure 4.** The CS sample chemical composition.

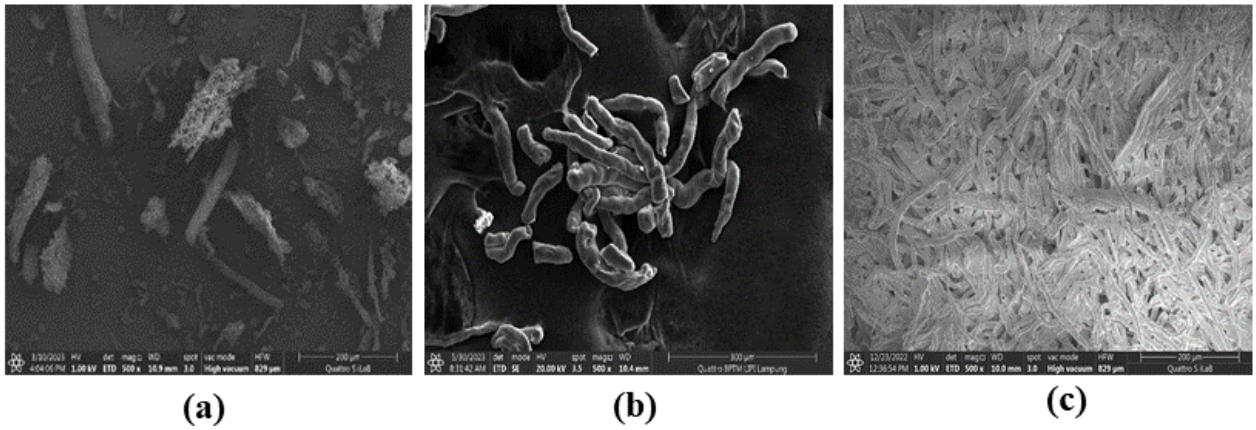


**Figure 5.** FTIR spectra of cellulose, lignin and hemicelluloses isolated from CS.

C/Alg/NC have a higher composition of crosslinking agents, Cu is 8.65% (Fig. 8) and Fe is 29.18% (Fig. 9).
It indicates the greatest absorption capacity of C/Alg/NC is the higher additional carbon on the composites due to its surface area. The activation of carbon has a well-defined porosity of various shapes and sizes, as well as the presence of various high-carbon functional groups for the removal of ions. (Ardiles and Rodrguez, 2021; Rui Rodrigues and Lagoa, 2006).

**Kinetic study of carbon/alginate/nanocellulose crosslinking with Cu and Fe**

The kinetic study was measured by varying the contact time from 2 to 5 days. After 1 day, the C/Alg/NC-Cu began to release Cu metal (Fig. 10). The 1:3:1 C/Alg/NC-Cu composite released less Cu for the first day at 0.05 mg/g, but

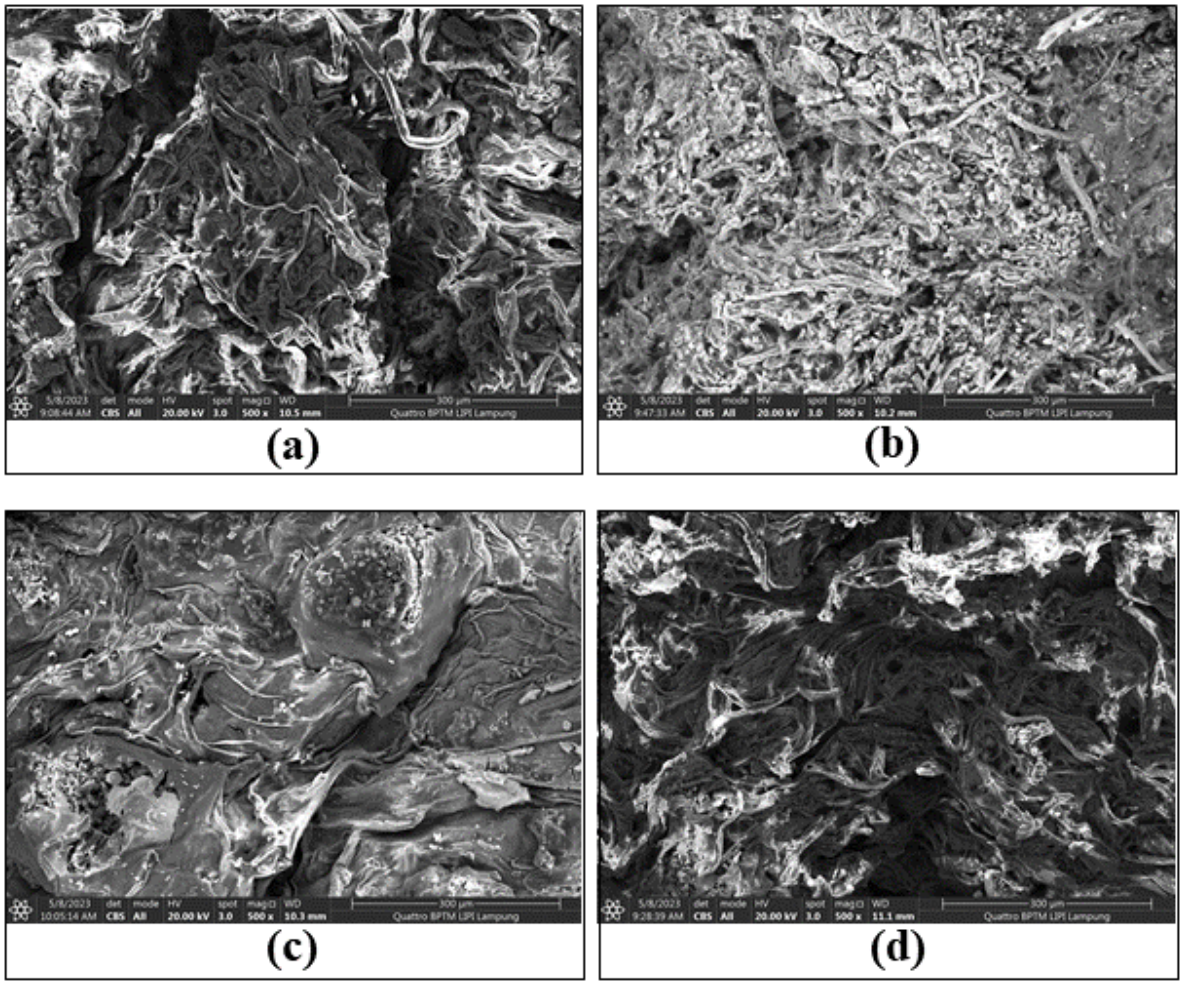


**Figure 6.** The biofertilizer pellets obtained.

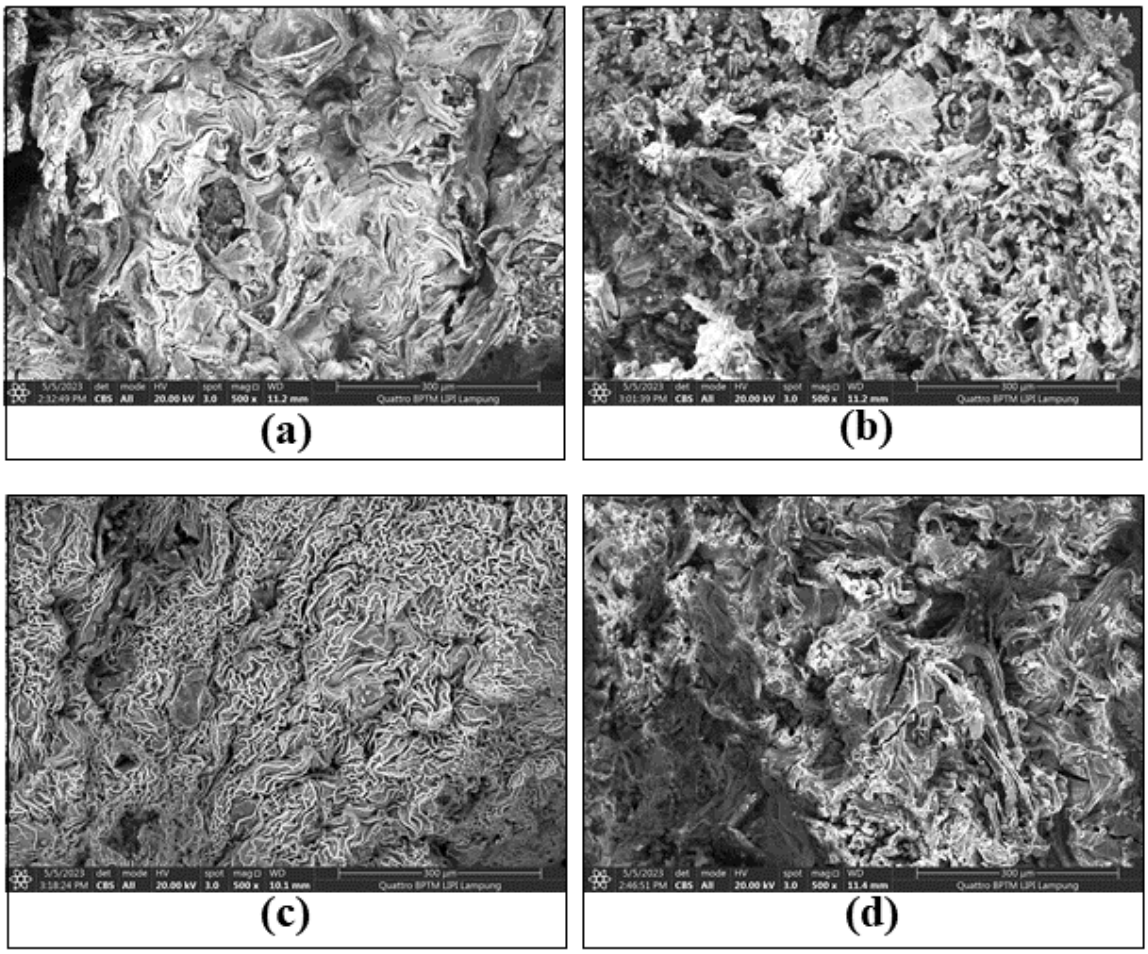


**Figure 7.** The CS sample chemical composition.

after two days, it released a very high amount of Cu at 0.6 mg/g and kept stable for up to five days, allowing it to operate as fertilizer, where Cu was released slowly but in larger quantities. The large drop in the intensity of the C=C and O-H groups shown in FTIR data on this compound reduces its capabilities as a slow-release fertilizer.

A considerable amount of alginate was not an effective technique for creating slow-release fertilizer using Cu metal. The same phenomenon occurred for the 1:1:3 C/Alg/NC-Cu composite; it released Cu slowly after two days, about 0.1 mg/g, but then rapidly after three days, reaching 0.3 mg/g, then stayed stable for up to five days. The 1:1:1 C/Alg/NC-Cu composite released the most Cu after 1 day at 0.2 mg/g, but it remained steady for 3 days before releasing more Cu after 4 and 5 days up to 5 mg/g, indicating this composite produced two gradual release phases. A similar phenomenon was found in the 3:1:1 C/Alg/NC-Cu composite; however, it released Cu in small amounts over two days, up to 0.05 mg/g, before increasing to 0.27 mg/g after five days. These two composites were better suited for use as slow-release fertilizer than the prior two composites. The higher carbon content in 3:1:1 C/Alg/NC-Cu resulted in an increase in C=C intensity from FTIR data, which proves to be formed due to the strong interaction between alginate and Cu ions.

Composites with Fe ion crosslinkers were comparable to Cu composites in that the excess composition of alginate and nanocellulose in the 1:3:1 C/Alg/NC-Fe and 1:1:3 C/Alg/NC-Fe composites did not improve the slow-release characteristics of Fe (Fig. 11). In only one day, the 1:3:1 C/Alg/NC-Fe composite released 0.44 mg/g of Fe, with more released gradually from the second day to the fourth day. Meanwhile, 1:1:3 C/Alg/NC-Fe released more extreme Fe, but it only reached 0.5 mg/g after two days, and Fe was slowly released after three and four days.

Meanwhile, the excess carbon composition had the optimum delayed release qualities for Cu metal, while Fe metal released Fe slightly faster, at 0.22 mg/g after 3 days. Excess carbon content marginally improved its slow-release qualities. An intriguing phenomenon was noticed in the 1:1:1 C/Alg/NC-Fe composite, which had the same mix of carbon, alginate, and nanocellulose and was found to have the best qualities as a slow-release fertilizer. Fe ions were slowly released, at roughly 0.05 mg/g for up to three days, then slightly more Fe up to 0.3 mg/g for the next three days until day six, and subsequently released at the same rate until day nine. The optimum compound for slow-release fertilizer was 1:1:1 C/Alg/NC-Fe.

The use of carbon, nanocellulose, and alginate crosslinked with Fe and Cu solutions provided gradual control of the

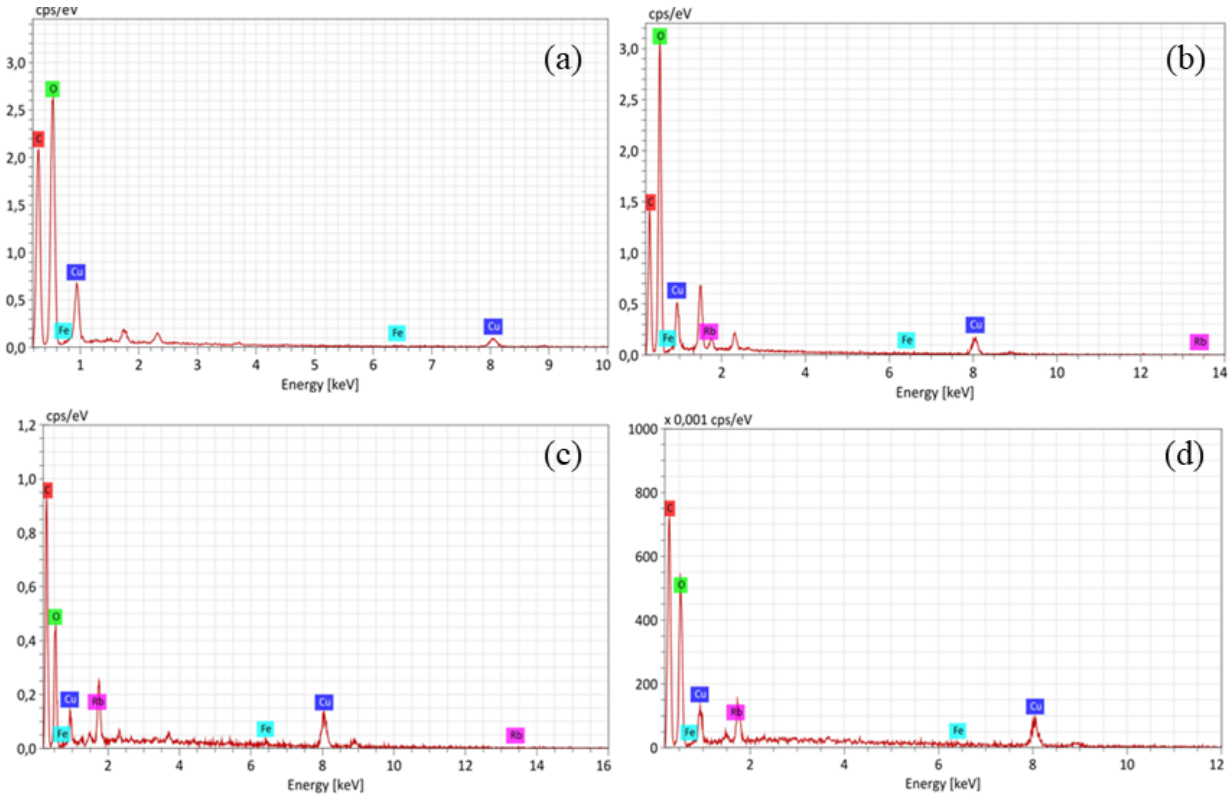


**Figure 8.** FTIR spectra of cellulose, lignin and hemicelluloses isolated from CS.

release of Fe and Cu nutrients. It will reduce the risk of excess nutrients at the beginning and allow plants to get a supply of Fe and Cu for a longer period of time. With slow release, plants can absorb Fe and Cu more efficiently without excess that has the potential to pollute the environment or be over-absorbed by plants. In addition, components such

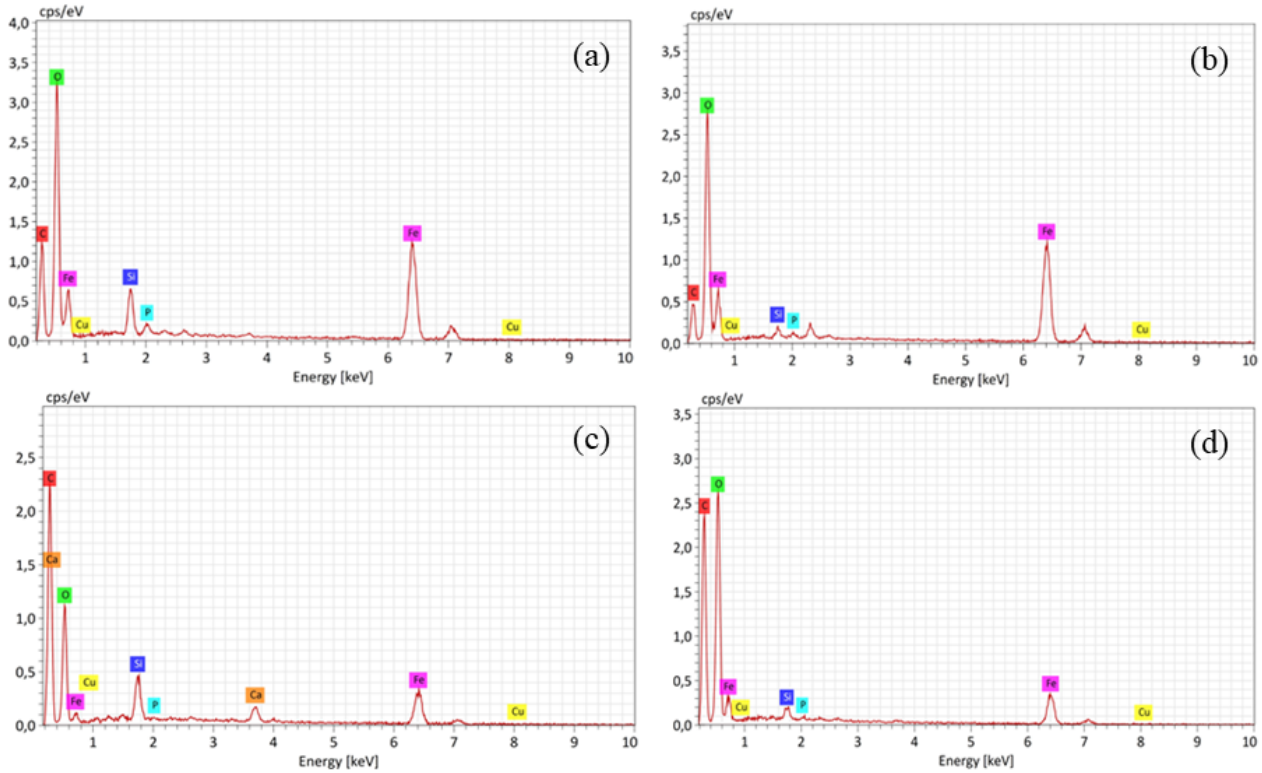


**Figure 9.** The biofertilizer pellets obtained.

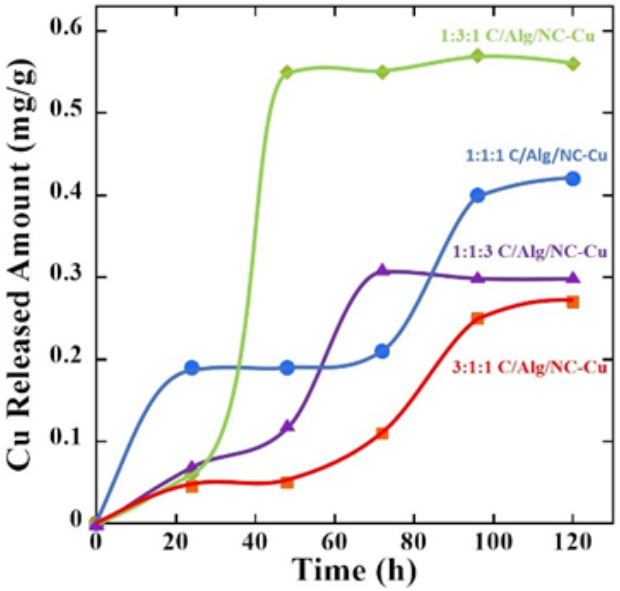


**Figure 10.** The CS sample chemical composition.

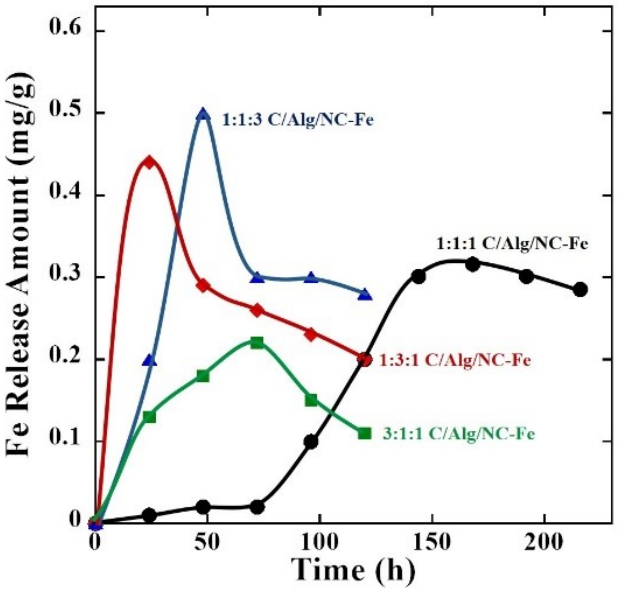


**Figure 11.** FTIR spectra of cellulose, lignin and hemicelluloses isolated from CS.

as nanocellulose and alginate are environmentally friendly materials and are easily degraded naturally, so they do not leave harmful residues in the soil. Crosslinking with alginate and Fe or Cu solutions allows a more stable and uniform distribution of Fe and Cu to the soil and plant roots. Then the presence of carbon in the composite can improve soil structure and help improving porosity, which allows for better root growth. The bond in the slow-release fertilizer composite plays an important role in controlled release and material stability.

Alginate, which is a natural polysaccharide, has carboxylic groups that can bind to $Fe^{2+}$ or $Fe^{3+}$ ions from Fe solutions and $Cu^{2+}$ from Cu solutions. These ionic bonds help forming a network structure that allows for slow release of Fe and Cu when the solution in the soil interacts with the composite. The crosslinking process with alginate creates a three-dimensional network that keeps carbon and nanocellulose in the matrix. This crosslinking not only provides mechanical strength but also controls the rate of nutrient release because the structure formed takes time to degrade or break down in the soil environment.

The presence of nanocellulose contains many hydroxyl groups (-OH) that can form hydrogen bonds with alginate. These hydrogen bonds increase cohesion between components and help maintaining the composite structure in soil conditions, while still allowing water to enter to initiate gradual release of Fe. If the carbon used in the composite has an aromatic structure such as activated carbon or graphite, there may be $\pi - \pi$ stacking interactions between the carbon layers and Fe and Cu ions, although this is usually not dominant compared to ionic or hydrogen bonds. If nanocellulose or carbon has been chemically modified, there has possibility to form additional covalent bonds formed between the functional groups added to the surface of these materials and Fe or Cu ions. These bonds provide mechanical and chemical stability to the composite, while allowing the slow release of Fe and Cu nutrients into the soil.

## 4. Conclusion

Introducing a crosslinker with Cu and Fe metals produced C/Alg/NC-Cu and C/Alg/NC-Fe composites by combining alginate with activated carbon and nanocellulose derived from solid waste from OPEFB. A composite with the same composition ratio of the three (1:1:1 C/Alg/NC-Fe) had the optimum slow-release capabilities for Fe metal; however, Cu metal had a greater carbon ratio, or 3:1:1 C/Alg/NC-Cu. Making composites from a combination of these three components can be a strategy for reusing OPEFB solid waste while also providing slow-release fertilizer that can be used as a source of plant nutrition in oil palm farms.

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**Authors contributions**

All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

**Availability of data and materials**

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

**Conflict of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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