

# Smart Hydrogels from Agro-Waste to Enhance Soil Water Retention for Climate-Resilient Agriculture

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Noah Adamtey, Owusu Abebrese, Godfred Y. Annum, Jonathan N. Hogarh



## The authors

**Noah Adamtey**, Senior Researcher - Resource Recovery and Agri-food System, International Water Management Institute (IWMI), Accra, Ghana

**Owusu Abebrese**, Senior Technician, Department of Environmental Science, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana

**Godfred Y. Annum**, Research Assistant, Department of Environmental Science, KNUST, Kumasi, Ghana

**Jonathan N. Hogarh**, Professor, Department of Environmental Science, KNUST, Kumasi, Ghana

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**Front cover photo:** Sapling corn on soil in a garden (*photo*: Freepik)

**Back cover photo:** Sugarcane bagasse (*photo*: Rizky Ade Jonathan)

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# Abbreviations

BC	Bacterial Cellulose (mentioned in the "Recommendations" section)
CaCl <sub>2</sub>	Calcium Chloride
CGIAR	Consultative Group on International Agricultural Research
CH	Coconut Husks
HCl	Hydrochloric Acid
IWMI	International Water Management Institute
KNUST	Kwame Nkrumah University of Science and Technology
NaOH	Sodium hydroxide
NaOCl	Sodium hypochlorite
PVA	Polyvinyl Alcohol
RH	Rice Husk
RS	Rice Straw
SCB	Sugarcane Bagasse
ZnCl <sub>2</sub>	Zinc Chloride

# Summary

Intensive agriculture and heavy agrochemical use have boosted food production but at significant environmental cost, generating waste that emits greenhouse gases and contaminates water. Concurrently, water scarcity and climate-induced droughts threaten crop yields and food security. Superabsorbent hydrogels offer a promising solution by retaining large amounts of water, improving soil moisture, reducing irrigation needs, and enhancing nutrient efficiency. However, synthetic hydrogels are non-biodegradable and inaccessible to smallholders, underscoring the need for sustainable, bio-based alternatives from agricultural residues to combine water-saving benefits with affordability and environmental safety. This study explored the feasibility of synthesizing hydrogels from agricultural waste to enhance farming system resilience against input scarcity, water risks, and climate change. The objectives were to explore methods and assess the suitability and effectiveness of producing hydrogels from sugarcane bagasse (SCB), rice straw (RS), and coconut husks.

The experiments were conducted at the Department of Environmental Science Laboratory, Kwame Nkrumah University of Science and Technology. The agro-wastes, SCB, RS and CH, which are lignocellulosic materials, were alkaline-delignified to expose the cellulose. The cellulose was then modified into carboxymethyl cellulose (CMC), which increases its capacity to form a more functional, water-swallowable, and reactive hydrogel. Specific protocols for the synthesis of ionic and covalent cross-linked hydrogels were explored to maximize hydrogel yield.

Ionic crosslinking followed by single crosslinking of SCB and RS yielded 36.69 g and 30.80 g of hydrogel (wet weight), respectively, this is equivalent to 14.68 and 12.32 metric tons per ton of SCB or RS. Ionic crosslinking with double covalent crosslinking produced 32.42 g and 25.94 g of hydrogel from SCB and RS, corresponding to 12.97 and 10.38 metric tons per ton of biomass.

The authors recommend that SCB should be prioritized for hydrogel synthesis where high yield is required, particularly under complex crosslinking conditions. Ionic crosslinking followed by single crosslinking is best suited for producing bulk hydrogel mass, while double covalent crosslinking should be selected for applications emphasizing functional performance, such as moisture retention and controlled release. Trade-offs between yield and functionality should guide hydrogel synthesis decisions. Further research should focus on expanding biomass-based and microbial synthesis approaches and improving drying methods for hydrogel production.

# 1. Introduction

Intensive agricultural practices and the high use of agrochemical have boosted production, which generates substantial volumes of waste that often end up in landfills, releasing greenhouse gases and contaminating surface water bodies, thereby posing significant public health and environmental risks (Bhatia., et al., 2024). Conventional waste-management methods such as open burning, landfilling, and chemical treatment are labour-intensive, costly, energy-demanding, and environmentally harmful (Ferronato and Torreta, 2019; Vaverková 2019; Kang et al., 2023; Anokye et al., 2024). Land degradation further exacerbates these challenges, particularly in tropical regions, where loss of soil organic matter and nutrient, biodiversity decline, altered hydrological cycles, and reduced soil water-holding capacity undermine ecosystem health and productivity (Olsson et al., 2019).

In sub-Saharan Africa where an estimated 85–90% of agriculture, 70% of employment, and 40% of exports depend on rainfall (Onwujekwe & Ezenba, 2021), limited water access severely impacts crop yields, food security, nutrition, and overall development (Abosedo, 2022). This situation is expected to worsen as global warming intensifies drought frequency and severity in agroecosystems (Abosedo, 2022).

Synthetic superabsorbent acrylic polymers (hydrogels) are a three-dimensional network of polymer chains that can absorb and retain large volumes of water relative to their mass, often absorbing water up to hundreds of times their weight, without dissolving (Li et al., 2021; Singh et al., 2021). When hydrogels are added to the soil, they absorb water from irrigation or rainfall and release it slowly over time, providing a continuous source of hydration and nutrients to meet the crop demand (Loo et al., 2021). These qualities make hydrogels particularly valuable in water-scarce regions, where they improve agricultural water use efficiency by helping to maintain soil moisture, reduce irrigation needs and support crop yields in drought-prone regions (Zhu et al., 2024). Additionally, hydrogels deliver pesticides or fertilizers in a controlled manner, help reduce nutrient leaching by retaining water-soluble nutrients and ensuring that the plants receive the required nutrients or protection over an extended period (Liu et al., 2022, Park et al., 2025). This improves nutrient-use efficiency and minimizes the environmental impacts of fertilizers by reducing runoff into nearby water bodies (Albalasmeh et al., 2022; Kaur et al., 2023). This helps to overcome the inefficiencies of rain-fed agriculture and ensuring sustainable farming (He et al., 2023).

Hydrogels also play a key role in environmental management by selectively absorbing pollutants such as heavy metals and dyes from wastewater. Functionalized variants, equipped with groups like carboxyl or amine, effectively chelate metal ions and act as superabsorbents for capturing and immobilizing contaminants in industrial and ecological cleanup applications (Pereira et al., 2021). While synthetic hydrogels offer several benefits as mentioned above, their non-biodegradable nature and limited accessibility to small-scale farmers present environmental and socioeconomic drawbacks. Their relatively long stability in the soil could potentially contribute to pollution of the soil and water system, and disrupting of the natural ecosystem (Bashir et al., 2020; Chen et al., 2022).

In contrast, effective water management solutions, including smart, environmentally friendly hydrogel systems, can enhance plant health and productivity by retaining water, regulating nutrient and pesticide release, and preventing environmental pollution. Those developed from organic waste could lead to a reduction in landfill waste, contributing to more sustainable consumption patterns (Mistry et al., 2023). This study aimed at exploring the feasibility of synthesizing hydrogels from agricultural waste to strengthen farming system resilience against input scarcity, water risks, and climate change. The objectives were to explore methods and assess the suitability, and effectiveness of synthesizing hydrogels from sugar cane bagasse, rice straw and coconut husks.

## 2. Materials and Methods

### 2.1. Materials

The study was conducted in the laboratory of the Department of Environmental Science, Kwame Nkrumah University of Science and Technology.

**Raw Materials:** Sugarcane Bagasse (SCB), Rice Straw (RS) and coconut husks.

**Chemicals:** Sodium Hydroxide (NaOH, 17% w/v), Monochloroacetic Acid, Acetic Acid, Ethanol, Zinc Chloride ( $ZnCl_2$ ), Calcium Chloride ( $CaCl_2$ ), Glutaraldehyde (25%), Polyvinyl Alcohol (PVA).

**Equipment:** Mechanical grinder, hot plate with magnetic stirrer, oven, desiccator, analytical balance, Buchner funnel, beakers, and suction filtration setup.

### 2.2. Methods

Two slightly different methods were assessed. The first method (labelled as Protocol A) was based on Mei et al. (2021), while a slight variation (labelled as Protocol B) was explored to maximize the yield of the hydrogel.

#### Protocol A

##### Pretreatment

Agro waste is lignocellulosic material and must be pretreated (usually with alkaline, and in some instances, followed by bleaching) to expose the cellulose, which is an important component for the hydrogel synthesis.

In this pretreatment, the agro wastes, sugarcane bagasse (SCB) and coconut husks (CH), were washed, dried at 70°C for 24 hours, and ground into a fine powder. 10 g of each biomass powder was delignified by alkaline treatment in 500 mL of 17% NaOH solution (Mei et al., 2021). Coconut husk samples were further bleached using 2% v/v Sodium Hypochlorite (NaOCl) for 30 minutes to remove residual lignin, pigments, and non-cellulosic impurities; to obtain a purer cellulose fraction.

##### Ionic Crosslinked Hydrogel

The pretreated, alkaline activated agro wastes were carboxymethylated to chemically modify the cellulose and increase its capacity to form a more functional, water-swallowable, and reactive hydrogel. The modified cellulose was treated with 5 g monochloroacetic acid in 500 mL ethanol, which helped to graft carboxymethyl groups onto the cellulose, producing carboxymethyl cellulose (CMC). The CMC powders (0.45 g and 0.50 g from bagasse and coconut husk, respectively) were each mixed in solution of 0.25 M  $CaCl_2$  and 0.50 M  $ZnCl_2$ , enabling  $Ca^{2+}$  and  $Zn^{2+}$  ions to form ionic bridges between adjacent carboxylate groups (ionic crosslinking), resulting in the formation of CMC hydrogels (Ban et al., 2021).

##### Single Covalent Crosslinked Hydrogel

The pretreated and alkali-activated agro-waste fibres were hydrolysed with 1 M HCl and filtered. The solid cellulose-rich fraction was then immersed in 300 mL of 25% glutaraldehyde at 60 °C for 1 hour to induce covalent cross-linking (Ban et al., 2021). The cross-linked hydrogel was allowed to stand overnight to dry. Single glutaraldehyde cross-linking creates a strong, stable, and uniform covalent polymer network that resists dissolution, maintains mechanical integrity, and offers reliable swelling and adsorption performance.

### Double Covalent Crosslinked Hydrogel

The alkaline activated cellulose sample prior to the ionic cross-linking stage was mixed with a Polyvinyl Alcohol (PVA) solution (0.015 g in 3 ml) and then reacted with glutaraldehyde (as in the single covalent crosslinked process above) to generate an interpenetrating polymer network culminating in a double covalent crosslinked enhanced hydrogel (Ban et al., 2021; Gong, 2003; Hassan et al., 2012).

### Protocol B

#### Pretreatment

Sugarcane bagasse and Rice Straw (RS) fibre were pretreated in a procedure like that outlined in Protocol A, except that 50 g of each biomass powder was activated in 500 mL of 2% w/v NaOH solution to form alkali cellulose.

#### Ionic Crosslinked Hydrogel

The point of divergence from Protocol A was that 50 mL of ethanol (and not 500 mL) was applied. Also, 2.5 g of the CMC powder (instead of the approximately 0.5 g used in Protocol A) was taken and cross-linked by immersing it in the mixture solution of 0.25 M  $\text{CaCl}_2$  and 0.5 M  $\text{ZnCl}_2$ . Using a relatively greater amount of waste fiber and reduced volume of reagent was expected to maximize yield at a reduced cost.

#### Single Covalent Crosslinked Hydrogel

Similar to the process described in Protocol A, but 50 mL of 5% glutaraldehyde solution was applied.

#### Double Covalent Crosslinked Hydrogel

The alkaline activated cellulose sample prior to the ionic cross-linking stage in Protocol B was mixed with a Polyvinyl Alcohol (PVA) solution (0.015g in 3ml) and then reacted with glutaraldehyde (as in the single covalent crosslinked process in Protocol B) to generate the double covalent crosslinked hydrogel.



(a) Coconut husk

(b) Sugarcane bagasse

(c) Rice straw

**Figure 1.** Ground agro-waste material used for hydrogel synthesis (*photo: Owusu Abebrese, KNUST*)

# 3. Results

## 3.1 Hydrogel Mass Yield from Protocol A

The results showed that 0.45 g of sugarcane bagasse (SCB) yielded 9.70 g of initial hydrogel (Table 1, Figure 1). In contrast, 0.50 g of coconut husk (CH) produced only 4.21 g (Figure 2b). When CH was single-crosslinked, the hydrogel yield was 63% higher than that obtained from SCB. Conversely, the hydrogel synthesized from SCB under double crosslinking was 3.5 times greater than that from CH. This could be attributed to watery formation during a single cross-linking (Figure 2b).

**Table 1.** Mass of hydrogel synthesized sugar cane bagasse and rice straw (Protocol A)

Raw material used	Wet weight of raw material	Wet weight of hydrogel (ionic cross-linked)	Wet weight of hydrogel (single crosslinked)	Wet weight of hydrogel (double crosslinked )
	(g)	(g)	(g)	(g)
Sugarcane Bagasse	0.45	9.70	5.60	5.17
Coconut husks	0.50	4.21	9.13	1.49



(a) Sugarcane bagasse hydrogel



(b) Coconut husk hydrogel

**Figure 2.** A hydrogel synthesized from sugar cane bagasse and coconut husks (photo: Owusu Abebrese, KNUST)

## 3.2 Hydrogel Mass Yield (Protocol B)

The results showed that under ionic crosslinking, sugarcane bagasse (SCB) yielded 44.5 g, which was 34% higher than the yield from rice husks (RH) (Table 1). Similarly, under single and double covalent crosslinking, the yields from SCB were 19% and 25% higher than those from RH, respectively. However, the yields from SCB under single and double covalent crosslinking were 21.5% and 37.5% lower than the yields obtained under ionic crosslinking. The same trend was observed for RH. For both materials, the hydrogel produced through single crosslinking was heavier than that from double crosslinking.).

**Table 2.** Mass of hydrogel synthesized from sugarcane bagasse and rice straw (Protocol B)

Raw material used	Wet weight of raw material	Wet weight of hydrogel (ionic cross-linked)	Wet weight of hydrogel (single crosslinked)	Wet weight of hydrogel (double crosslinked )
	(g)	(g)	(g)	(g)
Sugarcane Bagasse	2.5	44.57	36.69	32.42
Coconut husks	2.5	33.24	30.80	25.94



**Figure 3.** A hydrogel synthesized from rice straw (*photo: Owusu Abebrese, KNUST*)

## 4. Discussion

The comparative analysis of sugarcane bagasse (SCB), coconut husk (CH), and rice husks (RH) under different crosslinking methods provides critical insights into hydrogel synthesis. SCB consistently yielded more hydrogel than CH and RS across all methods, particularly under ionic crosslinking, likely due to its lower lignin content (20–21%) and simpler structure with  $\beta$ -O-4 ether linkages (Umasarayanan et al., 2011). This facilitates pretreatment (cellulose and hemicellulose dissolution) compared to CH, which contains more condensed lignin (30–50%) and C-C bonds ( $\beta$ -O-4 aryl ether), and RS, which has G-rich lignin (up to 36.1%) with C-C crosslinks ( $\beta$ -5, 5-5), making them more recalcitrant (Umasarayanan et al., 2011; Latif et al., 2017). Consequently, CH may require more aggressive or specialized pretreatment methods, such as low-cost ionic liquids, to break its condensed structure (Anuchi et al., 2022). In contrast, CH performed better under single crosslinking, producing a 63% higher yield than SCB, while SCB dominated under double crosslinking with a 3.5-fold increase over CH. These variations may be attributed to the watery formation observed during single crosslinking for CH, and further illustrate the interplay between material structure and hydration behavior.

Although single and double covalent crosslinking reduce hydrogel weight, they introduce structural features that enhance functional performance, making them ideal for applications where moisture retention and controlled release are prioritized over bulk mass. While structural compaction lowers hydrogel yield, covalent crosslinking improves mechanical stability, influencing dry/bulk density, swelling behavior, and water release (Bashir et al., 2020). Higher crosslink density typically limits maximum swelling because tighter networks restrict water accommodation within polymer chains (Hoti et al., 2021). However, studies show that combining covalent crosslinking with other design strategies, such as introducing hydrophilic groups, creating macroporosity, or adding porous inorganic/organic fillers, can produce hydrogels that are both structurally stable and exhibit enhanced water absorption, retention, and controlled release (Kasimu et al., 2024). In these systems, the covalent network provides mechanical integrity, while porosity, hydrophilicity, and fillers increase water uptake and slow release.

Overall, the results highlight the influence of biomass composition and crosslinking strategy on hydrogel properties. Optimizing hydrogel synthesis requires balancing yield and functional properties. SCB is more suitable for applications requiring high yield under complex crosslinking conditions, while CH may be advantageous where enhanced water absorption is critical. These findings underscore the importance of selecting biomass and crosslinking methods tailored to specific applications, such as soil conditioning, water retention systems, and controlled release technologies.

### 4.1 Limitations

The study relied exclusively on oven-drying at 60 °C to a constant weight for final hydrogel recovery. While this method is convenient for calculating mass yield, it can collapse the delicate porous network of the hydrogel, irreversibly reducing its surface area and water absorption capacity under high temperature. The investigation was limited to chemical synthesis methods (ionic and covalent crosslinking), which are relatively costly. Alternative approaches using biological synthesis pathways—such as bacterial cellulose production (e.g., *Komagataeibacter xylinus*) or enzymatic crosslinking (e.g., laccases)—were not explored. Only three agro-waste types were tested. The performance of Protocol B with other abundant and structurally distinct feedstocks (e.g., wheat straw, corn stover) remains unverified, restricting the generalizability of the findings. The difficulty in converting the synthesized hydrogels into a stable powder following the final drying stage, may affect downstream processing and application.

## 5. Conclusion and recommendations for future study

Single cross-linking of 2.5 g sugarcane bagasse (SCB) and rice straw (RS) yielded 36.69 g and 30.80 g of hydrogel (wet weight), respectively, equivalent to 14.68 and 12.32 metric tons of wet hydrogel per ton of SCB or RS. Based on the findings, SCB should be prioritized for hydrogel synthesis where high yield is required, particularly under complex crosslinking conditions. Coconut husk (CH), despite its lower yield under ionic crosslinking, is recommended for applications that demand superior water absorption and release properties. Ionic crosslinking is best suited for producing bulk hydrogel mass, while single and double covalent crosslinking should be selected for applications emphasizing functional performance, such as moisture retention and controlled release. The trade-off between yield and functionality must guide synthesis decisions. Incorporating additional crosslinkers such as PVA should aim to enhance structural and functional properties through design strategies like the introduction of hydrophilic groups and porous inorganic/organic fillers (e.g. activated charcoal) to improve hydrogel stability, water absorption, retention, and controlled release, rather than simply increasing yield. Further optimization of crosslinker concentrations and reaction conditions is recommended, along with pre-treatment strategies to reduce lignin interference in coconut husk (CH) and rice husks (RH). For application, specific synthesis, covalent crosslinking should be prioritized for agricultural water retention systems, whereas ionic crosslinking with sugarcane bagasse (SCB) is ideal for large-scale hydrogel production.

Drying methods also require evaluation; the current oven-drying approach should be compared with gentler techniques such as freeze-drying (lyophilization), which removes water via sublimation under vacuum to prevent pore collapse and preserve hydrogel structure. Additionally, a comparative study should focus on synthesizing bacterial cellulose (BC) hydrogels using *Komagataeibacter xylinus* fermented on agro-waste, with direct comparison of properties, such as purity, crystallinity, and water retention, against chemically crosslinked hydrogels.

Biomass selection should be broadened to include detailed compositional analysis of lignin, cellulose, and hemicellulose content, correlating these parameters with hydrogel yield and performance to develop predictive models for raw material selection. The hydrogel's effectiveness in water absorption and release should be tested both with and without crops, as well as its stability under varying temperature regimes. Finally, an economic feasibility assessment comparing chemical synthesis approaches with microbial methods is essential to guide cost-effective hydrogel production strategies.



Twisted straw remains field after harvesting cereal. (*photo*: freepik)

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Piled coconut husk (photo: Freepik)



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**Contact**

Noah Adamtey, Senior Researcher - Resource Recovery and Agri-food System, International Water Management Institute (IWMI), Accra, Ghana ([n.adamtey@cgiar.org](mailto:n.adamtey@cgiar.org))



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