

Original Research Article

Circular bio-activation of diaper-derived hydrogel into planting media: Determining agronomic pH stability through decentralized waste valorization

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ABSTRACT

The increasing consumption of disposable diapers has generated a persistent polymer-rich waste stream that remains largely excluded from circular recovery systems, particularly in regions where decentralized solutions are required. This study investigates the feasibility of converting diaper-derived hydrogel into planting media through microbial bio-activation and integration with locally available organic residues. A laboratory-scale experimental design was employed using seven formulations with hydrogel contents ranging from 400 to 1200 g and constant proportions of soil, rice husk charcoal, and nutmeg distillation residue. All media were fermented using Local Microorganism (LMO), and substrate pH was monitored weekly for four weeks as the primary indicator of agronomic suitability. The results show that all formulations produced near-neutral pH values between 6.3 and 6.5, with the most stable performance observed in the 800–500 g hydrogel range. These values fall within the optimal pH range for most crops, indicating that diaper-derived hydrogel can function as a water-retention component without inducing soil acidity when biologically stabilized. The study provides experimentally grounded evidence for a low-technology circular innovation that transforms sanitary waste and agro-industrial residues into productive agricultural inputs at the household and community scale.

Keywords: *Diaper waste valorization; hydrogel reuse; circular agriculture; microbial bio-activation; planting media; decentralized circular systems.*

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INTRODUCTION

The accelerating generation of municipal solid waste has intensified global concern regarding the environmental consequences of linear consumption patterns, particularly in rapidly urbanizing regions where waste management systems are under significant pressure (Ghisellini et al., 2016; Kirchherr et al., 2017). Among the most problematic components of domestic waste are disposable diapers, which are designed for single use yet composed of durable materials that persist in the environment for extended periods. Life-cycle assessments have shown that disposable diapers generate substantial environmental burdens due to raw-material extraction, manufacturing, and end-of-life disposal, while their composite structure—typically consisting of polyethylene films, cellulose pulp, elastics, adhesives, and superabsorbent polymers (SAP)—makes conventional recycling technically complex and economically unattractive (Aumônier et al., 2008; Cordella et al., 2015; Bellaby, 2022). Consequently, the majority of used diapers are disposed of in landfills or open dumping sites, where they contribute to long-term environmental pollution and represent a significant loss of potentially valuable material resources. This situation highlights the need for circular strategies that can operate at decentralized scales and transform sanitary waste into functional inputs for productive systems.

The circular economy provides a systemic framework for shifting from disposal-oriented waste management toward regenerative resource cycles by retaining material functionality and extending resource productivity (Geissdoerfer et al., 2017; Korhonen et al., 2018). Rather than focusing exclusively on industrial recycling technologies, contemporary circular-systems innovation increasingly emphasizes functional repurposing, in which materials are redirected into new applications that utilize their intrinsic properties and maintain their highest possible value (Stahel, 2016). This approach is particularly relevant for complex household waste streams that are difficult to process in centralized facilities but contain components with high functional potential. In this context, superabsorbent hydrogels from disposable diapers represent a promising yet underutilized resource. These cross-linked hydrophilic polymers are capable of absorbing and retaining water many times their own weight, a characteristic that closely resembles that of commercial soil conditioners used in horticulture to improve water availability, enhance plant growth, and reduce irrigation frequency (Zohuriaan-Mehr & Kabiri, 2008; Montesano et al., 2015).

At the same time, the development of alternative planting media has become a key component of sustainable agriculture, especially in urban and peri-urban environments where fertile soil is limited. Organic residues such as rice husk charcoal, compost, and agro-industrial by-products have been widely investigated as substitutes for conventional soil because they improve aeration, increase moisture retention, and support microbial activity while simultaneously contributing to circular resource utilization by diverting biomass from disposal pathways (Gruda, 2019; Lehmann & Joseph, 2015). However, the incorporation of unconventional materials into growing media requires careful evaluation of physicochemical properties, particularly pH, which plays a critical role in determining nutrient availability, microbial metabolism, and plant performance. Most horticultural crops require a pH range



between 6.0 and 7.0 for optimal growth because this interval maximizes nutrient solubility and biological activity in the rhizosphere (Marschner, 2012; Raviv & Lieth, 2008).

Biological stabilization through microbial fermentation is a widely used method for improving the quality of organic substrates. During the composting and maturation process, microbial inoculants accelerate the decomposition of organic matter, regulate acidity, and promote the formation of stable humic substances with buffering capacity (Bernal et al., 2009). In smallholder and community-based agricultural systems, locally produced microbial cultures—commonly referred to as Local Microorganism (LMO)—are frequently used because they are low-cost, readily available, and adapted to local environmental conditions. Such locally embedded bio-activation strategies are consistent with decentralized circular-economy models that strengthen regional resource loops while reducing dependence on external inputs (Schroeder et al., 2019). When applied to hybrid substrates that combine organic residues and polymer-based materials, microbial activity is expected to play a decisive role in determining the stability and agronomic suitability of the resulting planting media.

Despite the growing body of literature on circular agriculture and alternative growing media, empirical studies examining the direct transformation of disposable diaper components into agricultural substrates remain extremely limited. Existing research has primarily focused on life-cycle assessment, incineration, and partial material recovery at industrial scale, approaches that are often economically and technically inaccessible in developing regions (Cordella et al., 2015). Conversely, studies on hydrogel applications in agriculture have largely relied on virgin polymer materials specifically manufactured for soil conditioning (Montesano et al., 2015). The intersection between sanitary-waste valorization, microbial bio-activation, and growing-media development therefore represents an important but underexplored research domain.

This study addresses this gap by experimentally evaluating the integration of hydrogel extracted from disposable diaper waste into planting media through microbial bio-activation and the use of locally available organic residues. Seven formulations were prepared by varying the hydrogel mass while maintaining constant proportions of soil, rice husk charcoal, and nutmeg distillation residue. All formulations were fermented using LMO and monitored over a four-week period to assess pH stability as the primary indicator of agronomic suitability. By systematically analyzing the relationship between hydrogel content and substrate acidity, the study aims to determine the formulation range that produces the most stable and plant-compatible growing medium.

The findings of this study contribute to the literature in three significant ways. First, they provide experimental evidence that diaper-derived hydrogel can be functionally repurposed as a water-retention component in planting media without inducing undesirable changes in soil pH when biologically stabilized. Second, they identify the hydrogel incorporation range that yields the most stable agronomic conditions, thereby offering a practical formulation guideline for decentralized circular agriculture. Third, the study advances a circular bio-activation model that integrates sanitary waste, agro-industrial residues, and indigenous microbial processes into a regenerative production system that can be implemented at the household or community scale.



The remainder of this article is structured as follows. Section 2 presents a critical review of the literature on circular economy strategies for household waste, the environmental challenges associated with disposable diapers, the development of alternative growing media, and the role of microbial bio-activation in substrate stabilization. Section 3 describes the experimental design, material preparation, and analytical procedures. Section 4 reports the empirical results of the pH monitoring across the seven formulations. Section 5 discusses the implications of these findings for circular systems innovation, decentralized waste management, and sustainable agriculture. Finally, Section 6 concludes the article by summarizing the main contributions and outlining directions for future research on agronomic performance, environmental safety, and scaling potential.

LITERATURE REVIEW

2.1 Circular Economy and Decentralized Waste Valorization

The circular economy has emerged as a transformative paradigm for addressing the environmental and resource challenges associated with linear production and consumption systems. It promotes the retention of material value through reuse, repurposing, remanufacturing, and recycling while minimizing waste generation and environmental degradation (Kirchherr et al., 2017; Korhonen et al., 2018). Early circular-economy discourse primarily focused on industrial ecosystems and closed-loop manufacturing; however, more recent developments emphasize the importance of decentralized circular systems that operate at the household and community scale. Such systems are particularly relevant in developing regions, where centralized recycling infrastructure is limited and localized material loops can significantly reduce environmental burdens while creating new socio-economic opportunities (Prendeville et al., 2018; Schroeder et al., 2019).

Decentralized waste valorization represents a critical pathway within this framework. Instead of transporting heterogeneous waste streams to large processing facilities, locally available materials are transformed into productive inputs using low-technology and low-cost processes. This approach reduces transportation-related emissions, minimizes infrastructure dependency, and enables community-based circular innovation while simultaneously closing local resource loops (Ghisellini et al., 2016). Household waste streams that are widely generated but poorly managed—such as sanitary waste—are increasingly being recognized as potential resources for decentralized circular systems.

2.2 Environmental Challenges of Disposable Diaper Waste

Disposable diapers constitute a rapidly growing fraction of municipal solid waste due to demographic change, urbanization, and shifting consumption patterns (Cordella et al., 2015; Bellaby, 2022). Their environmental impact is particularly significant because of their composite structure and long degradation time, which can extend for decades or even centuries under landfill conditions (Aumônier et al., 2008). The multi-layered design, combining plastics, cellulose, and superabsorbent polymers, makes conventional recycling technically complex and economically unattractive.



Most existing waste-management strategies for disposable diapers rely on landfilling or incineration. Landfilling leads to long-term environmental persistence and potential leachate generation, while incineration requires high capital investment and raises concerns related to atmospheric emissions and ash disposal (Arena et al., 2016). Mechanical and chemical recycling methods have been explored, but these approaches generally depend on advanced separation technologies and centralized facilities that are rarely available in developing regions.

An alternative approach is functional repurposing, which involves redirecting specific components of the product into new applications that utilize their inherent properties. This strategy aligns with higher-value circular pathways (Stahel, 2016) because it preserves the functional characteristics of the material rather than breaking it down into lower-value forms.

2.3 Superabsorbent Hydrogels and Their Agricultural Potential

Superabsorbent polymers are hydrophilic cross-linked materials capable of absorbing and retaining water many times their own weight due to osmotic pressure and polymer-network elasticity (Zohuriaan-Mehr & Kabiri, 2008). In agriculture and horticulture, hydrogels are widely used as soil conditioners to improve water-use efficiency, enhance seed germination, and increase plant survival under drought conditions. By storing water and releasing it gradually to the root zone, hydrogels reduce irrigation frequency and improve soil moisture stability (Ekebafe et al., 2011; Montesano et al., 2015).

Research on hydrogel applications in agriculture has demonstrated their positive effects on soil physical properties, including increased water-holding capacity, improved soil structure, and enhanced microbial activity (Ahmed, 2015). However, most studies have utilized virgin polymer hydrogels specifically manufactured for agricultural use. The potential use of post-consumer hydrogels—particularly those recovered from disposable diapers—remains largely unexplored. This gap is significant because the functional properties of diaper-derived hydrogels are comparable to those of commercial soil conditioners, suggesting a viable pathway for circular reuse.

The incorporation of hydrogels into soil or planting media must be carefully controlled. Excessive polymer content can lead to reduced aeration and increased compaction, while insufficient stabilization may result in undesirable chemical changes. One of the most critical parameters influenced by hydrogel addition is pH, which determines nutrient availability and microbial activity.

2.4 Alternative Planting Media in Circular Agriculture

The development of alternative planting media has become an important strategy in sustainable and circular agriculture. Organic residues and agro-industrial by-products such as rice husk charcoal, compost, coconut coir, and biochar have been widely studied as substitutes for conventional soil because they improve porosity, enhance moisture retention, and contribute to nutrient cycling while simultaneously providing a circular solution for organic-waste management (Gruda, 2019; Lehmann & Joseph, 2015). Biochar-based materials, for example, increase cation-exchange capacity, improve microbial habitat, and enhance soil



buffering capacity, thereby supporting long-term fertility and carbon sequestration (Agegnehu et al., 2017).

The performance of planting media is determined by a combination of physical, chemical, and biological properties. Among these, pH is a key indicator of agronomic suitability because it directly controls nutrient solubility and microbial metabolism. Most horticultural crops require a pH range between 6.0 and 7.0 for optimal growth, as this range ensures maximum nutrient availability and biological activity in the rhizosphere (Marschner, 2012; Raviv & Lieth, 2008). Substrates with pH values outside this range may limit plant development regardless of their physical characteristics.

Integrating unconventional materials such as polymer-based hydrogels into planting media requires empirical validation to ensure that the resulting substrate meets agronomic standards. This is particularly important in circular systems, where the objective is not only to reuse waste but also to produce functionally effective outputs.

2.5 Microbial Bio-Activation and Substrate Stabilization

Microbial fermentation is widely used in organic agriculture to stabilize organic matter and improve substrate quality. Microbial inoculants accelerate the decomposition of complex organic compounds, regulate acidity, and promote the formation of stable humic substances. The metabolic activities of microorganisms influence pH dynamics during fermentation, typically producing organic acids in the early stages, followed by gradual neutralization as the substrate matures.

Locally produced microbial inoculants, commonly referred to as Local Microorganism (LMO), are derived from plant materials and agricultural residues and are adapted to local environmental conditions. LMO-based fermentation is widely practiced in smallholder farming systems because it is inexpensive, easily produced, and environmentally compatible. In addition, these technologies have been shown to support sustainable farming systems by reducing dependence on external inputs while strengthening localized nutrient cycles (Xu et al., 2020) and reducing production costs.

The interaction between microbial activity and hybrid substrates containing both organic materials and polymer-based components is a relatively new research area. In such systems, microbial stabilization is expected to play a decisive role in regulating physicochemical properties, particularly pH, which determines the agronomic performance of the planting media.

2.6 Functional Repurposing in Circular Bio-Activation Systems

Functional repurposing represents a high-value circular strategy in which a material is used in a new application that exploits its inherent properties and maintains its functional integrity (Stahel, 2016). In the context of diaper-derived hydrogel, this strategy preserves the water-absorption capability of the polymer while integrating it into a biological production system. When combined with organic residues and microbial activation, the resulting substrate becomes part of a regenerative cycle in which waste is transformed into a productive resource.



This approach aligns with the concept of circular bio-activation systems, where biological processes are used to convert heterogeneous waste streams into stable and agronomically valuable materials (Geissdoerfer et al., 2017). Such systems are particularly relevant for decentralized implementation because they rely on locally available inputs and simple processing techniques.

2.7 Functional Repurposing in Circular Bio-Activation Systems

The literature indicates several important gaps. First, empirical studies on the direct integration of diaper-derived hydrogels into planting media are extremely limited, with most research focusing on life-cycle assessment or centralized recycling technologies (Cordella et al., 2015). Second, the relationship between hydrogel content and soil pH in biologically activated substrates has not been systematically examined. Third, the role of locally produced microbial inoculants in stabilizing hybrid organic–polymer media remains underexplored. Furthermore, studies on hydrogel application in agriculture have predominantly relied on virgin materials rather than post-consumer sources (Montesano et al., 2015)

To address these gaps, this study assumed that diaper-derived hydrogel can be functionally repurposed as a water-retention component in planting media when combined with organic residues and microbial bio-activation; that hydrogel incorporation within an appropriate formulation range does not induce undesirable changes in substrate pH level; that LMO-based fermentation produces stable near-neutral pH conditions suitable for plant growth; and that the stability of pH over time is a key indicator of agronomic suitability in circular planting-media systems.

These assumptions provide the theoretical foundation for the experimental investigation and position the study within the broader discourse on circular systems innovation, decentralized waste valorization, and regenerative agriculture.

METHOD

3.1 Research Design

This study employed a laboratory-scale experimental design to evaluate the feasibility of converting diaper-derived hydrogel into planting media through microbial bio-activation and integration with locally available organic materials. The experimental approach followed a controlled comparative formulation model in which the hydrogel mass was treated as the primary independent variable while all other components of the planting media were maintained at constant proportions. Such a controlled-factor design is widely used in material and agricultural experiments to isolate the effect of a single variable and to enable robust comparison among treatments (Montgomery, 2017). Substrate pH measured over time was used as the main indicator of agronomic suitability because it directly influences nutrient availability, microbial activity, and plant growth performance in soil and soilless media systems (Marschner, 2012; Raviv & Lieth, 2008).

Seven planting-media formulations were prepared and subjected to a standardized fermentation process using the local microorganism (LMO). The pH of each formulation was



monitored for four weeks to determine stabilization patterns and to identify the formulation range that produced the most suitable conditions for plant cultivation. The research flow diagram is presented in Figure 1.

3.2 Materials and Sample Preparation

3.2.1 Hydrogel Recovery from Disposable Diapers

Used disposable diapers were manually disassembled to extract the superabsorbent polymer (SAP) hydrogel component. Prior to extraction, diapers were cleaned to remove residual contaminants. The hydrogel fraction was separated from non-absorbent layers, air-dried, and weighed using a calibrated digital scale to ensure measurement precision. The recovery of SAP from absorbent hygiene products has been reported as a feasible approach for material valorization in experimental studies, provided that appropriate cleaning and handling procedures are applied (Bellaby, 2022). Hydrogel quantities were varied across experimental samples to assess proportional effects on substrate performance.

3.2.2 Organic Substrate Components

Each planting medium incorporated the following locally sourced materials and these materials were selected based on regional availability and relevance to circular agricultural practices in Aceh Selatan, Indonesia. The utilized material in the experimental are presented in Table 1.

Table 1. Organic substrate components

Material	Function	Reference
Topsoil	Serving as the primary structural base, providing mineral support and buffering capacity.	(Gruda, 2019)
Rice husk charcoal	Included to enhance aeration, increase porosity, and improve water-holding characteristics due to its biochar-like properties.	(Lehmann & Joseph, 2015; Agegnehu et al., 2017)
Nutmeg distillation residue	Utilized as an organic amendment rich in decomposable biomass capable of supporting microbial activity and humification processes.	(Bernal et al., 2009)
Banana-corm-derived local microorganisms (LMO)	Use as the biological activator because locally produced microbial inoculants have been widely applied in sustainable agriculture to accelerate decomposition and strengthen localized nutrient cycles.	(Higa & Parr, 1994; Xu et al., 2020)

3.3 Experimental Planting Media Formulations

Seven planting-media formulations were prepared by varying the hydrogel mass while maintaining constant quantities of soil, rice husk charcoal, and nutmeg distillation residue. All formulations were treated with LMO as the microbial activator. The composition of each formulation is presented in Table 2. Maintaining constant proportions of non-hydrogel components ensured that any variation in pH resulted from differences in hydrogel content, thereby supporting internal experimental validity (Montgomery, 2017).



Table 2. Composition of planting-media formulations.

Sample	Hydrogel (g)	Soil (g)	Rice Husk Charcoal (g)	Nutmeg Residue (g)	Microbial Treatment (g)
I	1200	1000	400	500	500 (LMO)
II	1000	1000	400	500	500 (LMO)
III	800	1000	400	500	500 (LMO)
IV	700	1000	400	500	500 (LMO)
V	600	1000	400	500	500 (LMO)
VI	500	1000	400	500	500 (LMO)
VII	400	1000	400	500	500 (LMO)

3.4 Fermentation and Stabilization Process

After homogenization, each formulation underwent a fermentation process for seven days. The mixtures were placed in closed containers to maintain moisture while allowing limited aeration for microbial activity. During fermentation, the media were periodically mixed to ensure uniform decomposition and even distribution of microorganisms. Controlled composting and fermentation processes are known to promote the transformation of unstable organic compounds into mature substrates with improved chemical stability and buffering capacity (Bernal et al., 2009)

The LMO solution was prepared from banana corm and applied uniformly to each formulation. At the end of the fermentation period, the planting media were transferred to open containers for the observation phase to allow stabilization under ambient conditions.

3.5 Data Collection and Measurement

Substrate pH was measured at five observation points: Week 0 (after fermentation), Week 1, Week 2, Week 3, and Week 4. A calibrated digital pH meter was used for all measurements. Prior to measurement, the media were homogenized to obtain representative readings. Determination of pH using an electrode in a homogenized substrate–water mixture is a standard method in soil and growing-media analysis (Thomas, 1996). Each measurement was conducted under the same environmental conditions to minimize external variability. The weekly pH values were used to calculate the average pH for each formulation and to analyze stabilization trends over time.

In addition to pH, qualitative observations were recorded, including moisture retention characteristics, Odor development, Visible fungal growth, Substrate texture, and aggregation. These observations provided contextual insight into substrate stability and decomposition dynamics which are commonly used as indicators of compost stability and biological activity (Bernal et al., 2009).

3.6 Data analysis

The data were analyzed using descriptive comparative techniques. The analysis focused on: Temporal pH trends for each formulation, Average pH values, Stability of pH over the



observation period, Identification of the formulation range that met the agronomic pH criterion (6.0–7.0). The most suitable planting media were determined based on the consistency of pH within the optimal range and the degree of stabilization throughout the four-week monitoring period. Descriptive analysis is appropriate for controlled experimental material studies aimed at identifying performance patterns among treatment groups (Montgomery, 2017).

To ensure measurement reliability, the study implement the following conditions:

- The pH meter was calibrated prior to each measurement session.
- All formulations were prepared using identical procedures.
- The mass of soil, rice husk charcoal, and nutmeg residue was kept constant.
- The fermentation period and environmental conditions were standardized.

Instrument calibration and procedural consistency are essential for reducing systematic error and improving measurement reliability in experimental research (Taylor, 1997). Internal validity was achieved by isolating the hydrogel mass as the only experimental variable.

3.7 Methodological Limitations

This study focused on pH as the primary indicator of agronomic suitability and did not include plant-growth trials, nutrient analysis, or long-term environmental impact assessment of the hydrogel in soil. Although pH is a master variable controlling nutrient availability and microbial activity, comprehensive agronomic validation requires additional physicochemical and biological parameters (Marschner, 2012).

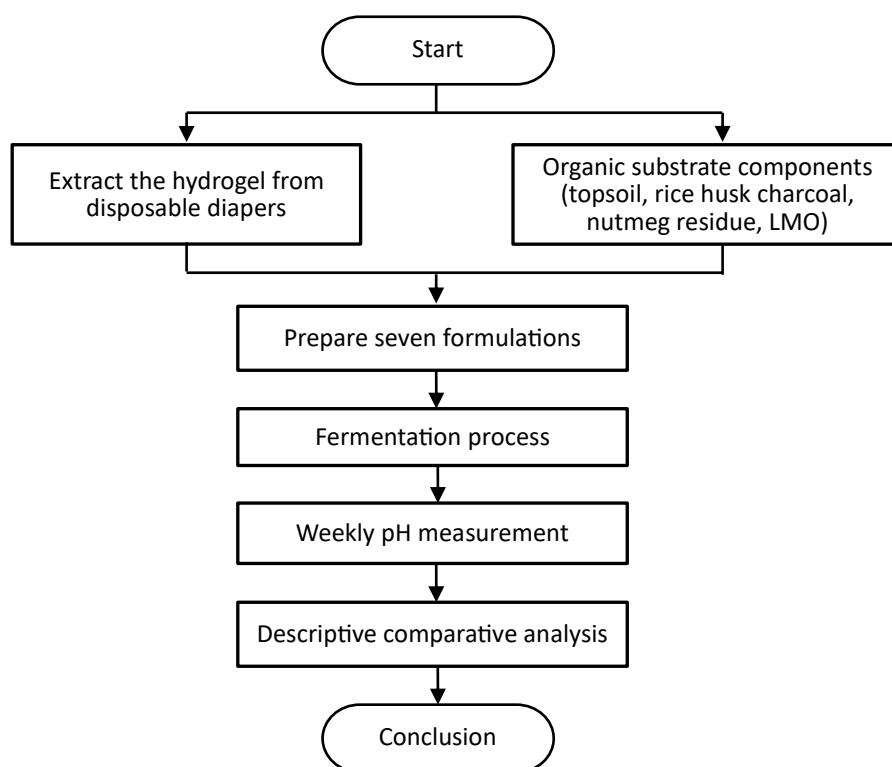


Figure 1. Research Flowchart diagram



RESULT

Seven planting-media formulations were successfully produced by integrating diaper-derived hydrogel with soil, rice husk charcoal, and nutmeg distillation residue in constant proportions and applying Local Microorganism (LMO) fermentation. The hydrogel mass was varied from 1200 g to 400 g to evaluate its influence on substrate pH stability over a four-week observation period. The primary performance indicator was pH, measured weekly from week 0 (after fermentation) to week 4.

4.1 Weekly pH Measurements

The complete dataset of weekly pH measurement results is presented in Table 2, and each sample is discussed in the following section.

4.1.1 Sample I (Hydrogel 1200 g)

The initial pH after fermentation was recorded at 6.5. A slight decrease to 6.3 occurred during week 1, followed by stabilization between 6.3 and 6.4 in weeks 2–4. The average pH value for this formulation was 6.4, indicating a near-neutral condition throughout the observation period.

4.1.2 Sample II (Hydrogel 1000)

The pH value at week 0 was 6.5 and remained within a narrow range between 6.3 and 6.5 during the four-week monitoring period. The average pH was 6.4, demonstrating a stable and agronomically suitable condition.

4.1.3 Sample III (Hydrogel 900 g)

Formulation SIII exhibited a similar pattern, with an initial pH of 6.5, a slight decrease to 6.4 in week 1, and stabilization at 6.4–6.5 in subsequent weeks. The average pH value was 6.5.

4.1.4 Sample IV (Hydrogel 800 g)

This formulation showed the most consistent pH profile. The pH remained at 6.5 for most of the observation period, with only minor fluctuation to 6.4 in week 2. The average pH was 6.5, indicating high stability.

4.1.5 Sample V (Hydrogel 700)

The pH ranged between 6.4 and 6.5 across all observation weeks. The average pH value was 6.5, demonstrating stable near-neutral conditions.

4.1.6 Sample VI (Hydrogel 500 g)

The pH values for this formulation were 6.4–6.5 throughout the observation period. The average pH was 6.5, indicating that reducing the hydrogel content to 500 g did not negatively affect substrate acidity.

4.1.7 Sample VII (Hydrogel 400 g)

The lowest hydrogel loading produced slightly lower pH values compared with the other formulations. The pH ranged from 6.3 to 6.4, with an average value of 6.3. Although still within



the acceptable agronomic range, this formulation showed the lowest stability among all treatments.

Table 3. pH measurements.

Sample	Week	pH	Average pH
I (Hydrogel 1200g)	0	6.7	6.5
	1	6.3	
	2	6.0	
	3	6.5	
	4	7.0	
II (Hydrogel 1000 g)	0	6.5	6.4°
	1	6.0	
	2	6.0	
	3	6.5	
	4	7.0	
III (Hydrogel 800g)	0	6.5	6.5
	1	6.4	
	2	6.1	
	3	6.7	
	4	7.1	
IV (Hydrogel 700 g)	0	6.5	6.5°
	1	6.5	
	2	6.0	
	3	6.5	
	4	7.0	
V (Hydrogel 600g)	0	6.5	6.4
	1	6.2	
	2	5.9	
	3	6.4	
	4	6.9	
VI (Hydrogel 500 g)	0	6.5	6.5°
	1	6.5	
	2	6.0	
	3	6.5	
	4	7.0	
VII (Hydrogel 400g)	0	6.4	6.3
	1	6.1	
	2	5.8	
	3	6.3	
	4	6.9	



4.2 Comparative pH Stability

All seven formulations produced near-neutral pH values within the agronomic suitability range of 6.0–7.0. However, differences in stability and average pH were observed.

- Highest stability: S4, S5, and S6 (800–500 g hydrogel) with an average pH of 6.5
- Moderate stability: S1 and S2 (1200–1000 g hydrogel) with an average pH of 6.4
- Lowest pH: S7 (400 g hydrogel) with an average pH of 6.3

The fluctuation range across all formulations was minimal, indicating consistent substrate stabilization during the observation period. The convergence toward near-neutral pH values over time is characteristic of biologically stabilized organic substrates, in which early-stage organic acid formation is followed by progressive neutralization during maturation (Bernal et al., 2009)

4.3 Agronomic Suitability

The experimental results show that varying hydrogel content within the tested range did not produce significant shifts in substrate acidity when LMO fermentation was applied. All formulations remained within the near-neutral pH range considered optimal for most horticultural crops (Marschner, 2012; Raviv & Lieth, 2008).

This pattern is consistent with findings in the soil-conditioning literature, which report that hydrogel incorporation generally has a neutral to slightly buffering effect on soil pH because the polymer network primarily functions as a physical water reservoir rather than a source of acidic or alkaline ions (Montesano et al., 2015; Zohuriaan-Mehr & Kabiri, 2008). The stable pH values observed in this study indicate that the diaper-derived hydrogel did not introduce chemical conditions that would disrupt the agronomic suitability of the planting media.

Therefore, based on the widely accepted optimal pH range for plant growth (6.0–7.0):

- All formulations met the agronomic suitability criterion.
- The most stable and optimal performance was observed in formulations with hydrogel contents between 800 g and 500 g.
- The lowest hydrogel content (400 g) produced slightly lower pH values, although still within the acceptable range

4.4 Summary of Experimental Performance

Overall, the experimental results indicate that:

1. LMO-based fermentation successfully stabilized all hydrogel–organic mixtures.
2. Hydrogel incorporation of 500 g - 800 g produced the most consistent near-neutral pH.
3. Increasing the hydrogel mass above 1000 g did not improve pH performance.
4. All formulations remained suitable for planting-media applications.

The stabilization of pH across the observation period suggests that the combination of organic residues and microbial activity created a buffered substrate environment, in which adequate moisture retention supported sustained microbial metabolism and gradual chemical equilibrium (Bernal et al., 2009; Lehmann & Joseph, 2015). These findings confirm that diaper-



derived hydrogel can be integrated into planting media without inducing undesirable changes in soil acidity when appropriate biological activation is applied.

DISCUSSION

5.1 Hydrogel Incorporation and pH Stability in Bio-Activated Planting Media

The experimental results demonstrate that diaper-derived hydrogel can be incorporated into planting media without causing significant shifts in substrate acidity when stabilized through LMO fermentation. All seven formulations produced near-neutral pH values within the agronomic suitability range (6.0–7.0), with only minor variation across the hydrogel incorporation spectrum. This finding indicates that the hydrogel acted primarily as a physical water-retention component rather than as a chemically reactive agent influencing soil acidity. The absence of strong pH deviation confirms that the polymer structure did not release acidic or alkaline ions in quantities sufficient to alter the chemical balance of the substrate, which is consistent with previous studies reporting that hydrogels function mainly as water-storage matrices with minimal direct chemical interaction with the soil solution (Montesano et al., 2015; Zohuriaan-Mehr & Kabiri, 2008).

The highest pH stability observed in formulations containing 800–500 g hydrogel suggests that adequate moisture retention supported more consistent microbial activity during the maturation phase. Sustained moisture availability is known to enhance microbial metabolism, accelerate humification, and promote the formation of stable organic compounds that buffer pH fluctuations in organic substrates (Bernal et al., 2009). In contrast, the slightly lower stability in the lowest hydrogel treatment indicates that insufficient water retention may limit microbial regulation of substrate chemistry.

The absence of further improvement at hydrogel contents above 1000 g indicates the presence of a functional incorporation threshold, beyond which additional material input does not generate proportional performance benefits. This outcome reflects the principle of material efficiency in circular systems, where optimal performance is achieved through appropriate rather than maximal resource use (Allwood et al., 2011). From a material-efficiency perspective, this finding is important because it demonstrates that moderate hydrogel quantities are sufficient to achieve agronomically suitable conditions

5.2 Role of LMO in Substrate Stabilization

The uniform application of LMO across all formulations provided a consistent bio-activation pathway that played a decisive role in stabilizing the hybrid organic–polymer media. Microbial fermentation typically involves a succession of metabolic phases in which organic acids produced during early decomposition are progressively neutralized as humified compounds are formed, resulting in a mature substrate with near-neutral pH (Bernal et al., 2009). The stabilization patterns observed in this study indicate that such a maturation process occurred successfully in all treatments.



The effectiveness of LMO in regulating pH can be attributed to its locally adapted microbial composition and its capacity to decompose organic residues such as nutmeg distillation waste and rice husk charcoal. The formation of humic substances during this process increases cation-exchange capacity and buffering potential, thereby enhancing chemical stability in the planting media (Lehmann & Joseph, 2015). The use of indigenous microbial inoculants also aligns with sustainable agricultural practices that emphasize the use of locally available biological resources to reduce dependence on external inputs and strengthen localized nutrient cycles (Xu et al., 2020).

5.3 Comparison with Hydrogel–Soil Interaction in Previous Studies

Studies on synthetic hydrogels used as soil conditioners generally report neutral or slightly buffering effects on soil pH because these polymers function as physical absorptive matrices rather than as chemical amendments (Ahmed, 2015; Montesano et al., 2015). The results of the present study are consistent with this body of knowledge, demonstrating that even when the hydrogel is derived from post-consumer sources, its incorporation does not induce harmful acidity or alkalinity when biologically stabilized.

Most previous research has focused on virgin hydrogels specifically manufactured for agricultural applications. By contrast, the present study demonstrates that hydrogel recovered from disposable diaper waste exhibits comparable functional behavior in terms of its influence on substrate pH. This finding supports the argument that post-consumer polymer materials can retain their functional properties when appropriately processed and integrated into bio-activated systems, thereby expanding the scope of circular material reuse (Bellaby, 2022).

5.4 Contributions to Circular Systems Innovation

This study contributes to circular systems innovation by providing experimental evidence for a decentralized model of sanitary-waste valorization. The transformation of diaper-derived hydrogel into planting media represents a high-value circular strategy because it preserves the functional properties of the material and integrates them into a regenerative biological cycle rather than down-cycling them into lower-value outputs (Geissdoerfer et al., 2017; Korhonen et al., 2018). The localized configuration of the process reduces the need for complex infrastructure and enables implementation at the household or community scale, which is a key characteristic of emerging circular-city and distributed-resource systems (Prendeville et al., 2018).

The integration of hydrogel with agro-industrial residues such as nutmeg distillation waste and rice husk charcoal further strengthens the circular character of the system by converting multiple waste streams into a single productive input. The use of LMO as a microbial activator eliminates dependence on commercial inputs and reinforces local resource loops, thereby aligning with circular-economy strategies that contribute to the achievement of broader sustainability goals (Schroeder et al., 2019).

5.5 Managerial and Policy Implications

From a practical perspective, the identification of an optimal hydrogel incorporation range has direct implications for community-based waste-valorization initiatives. The finding that



moderate hydrogel quantities (800–500 g) are sufficient to produce agronomically suitable planting media reduces the need for excessive material extraction and simplifies the production process. This supports resource-efficiency strategies that are central to circular-economy implementation (Allwood et al., 2011).

For policymakers, the results demonstrate that sanitary waste—traditionally considered non-recyclable—can be transformed into a productive resource through decentralized circular innovation. Supporting training programs, demonstration projects, and integration with urban-agriculture initiatives could facilitate the adoption of this approach and generate simultaneous benefits for waste management, local food production, and circular-economy literacy (Schroeder et al., 2019).

5.6 Formulation Optimization and Circular Material Integration

An important observation is that the lowest hydrogel incorporation (400 g) produced slightly lower pH values than the other formulations. This suggests that hydrogel not only functions as a water-retention material but also indirectly contributes to microbial stabilization by maintaining moisture balance. This indirect buffering effect has received limited attention in previous studies and warrants further investigation.

Another notable result is that increasing the hydrogel mass above 1000 g did not produce measurable improvements in pH stability. This finding highlights the importance of formulation optimization in circular material integration and demonstrates that higher material input does not necessarily lead to better performance (Allwood et al., 2011).

5.7 Limitations and Future Research

Several limitations must be acknowledged. First, the study focused exclusively on pH as the primary indicator of agronomic suitability and did not include plant-growth trials, nutrient-availability analysis, or long-term environmental assessment of the hydrogel in soil. Second, the laboratory-scale design does not fully represent field conditions, where environmental variability may influence substrate performance. Third, the study did not evaluate the physical properties of the planting media, such as bulk density, porosity, and water-holding capacity, which are also critical for plant growth.

Future research should therefore include controlled plant-growth experiments, comprehensive physicochemical characterization, and long-term monitoring of polymer stability in soil. Comparative studies involving different microbial inoculants and additional organic residues would further refine the formulation design. In addition, life-cycle assessment and techno-economic analysis are needed to evaluate the scalability and the environmental benefits in circular-economy transitions (Hauschild et al., 2018).

CONCLUSION

This study examined the feasibility of converting hydrogel recovered from disposable diaper waste into agronomically suitable planting media through integration with locally available organic residues and microbial bio-activation using Local Microorganism (LMO). By applying a



controlled laboratory-scale experimental design, seven formulations with hydrogel contents ranging from 1200 g to 400 g were produced and monitored over a four-week period to evaluate pH stability as the principal indicator of planting-media performance. The findings demonstrate that all formulations achieved near-neutral pH values between 6.3 and 6.5, which fall within the optimal range for most horticultural crops and therefore indicate favorable conditions for nutrient availability and biological activity (Marschner, 2012; Raviv & Lieth, 2008). These results confirm that diaper-derived hydrogel can be functionally repurposed as a water-retention component in planting media without inducing undesirable changes in substrate acidity when biologically stabilized.

The most stable and agronomically favorable conditions were observed in formulations containing 800–500 g of hydrogel. Within this range, the substrates exhibited minimal temporal fluctuation and consistently maintained an average pH of approximately 6.5. Increasing the hydrogel content above 1000 g did not produce additional improvements in pH stability, while the lowest hydrogel loading (400 g) resulted in slightly lower but still acceptable pH values. This outcome indicates that moderate hydrogel incorporation is sufficient to achieve optimal chemical conditions and that excessive polymer input does not enhance substrate performance. From a circular-material-efficiency perspective, this finding is significant because it demonstrates that optimal functionality can be achieved through appropriate rather than maximal resource use, which is a core principle of sustainable material management (Allwood et al., 2011).

The successful stabilization of all formulations highlights the critical role of LMO fermentation in regulating substrate acidity. The microbial decomposition of organic components, including nutmeg distillation residue and rice husk charcoal, contributed to the formation of humified compounds with buffering capacity, thereby ensuring near-neutral pH conditions and chemical stability (Bernal et al., 2009). This confirms that indigenous microbial inoculants can serve as an effective and low-cost bio-activation strategy for hybrid organic–polymer substrates in decentralized circular systems.

From a circular-economy and industrial-ecology perspective, the study provides experimentally grounded evidence that a persistent sanitary-waste stream can be transformed into a productive agricultural input through a low-technology, locally adaptable process. By preserving the intrinsic water-retention function of the hydrogel and integrating it into a regenerative biological cycle, the proposed approach represents a high-value circular pathway that extends beyond conventional recycling and aligns with value-retention strategies in circular production systems (Geissdoerfer et al., 2017; Stahel, 2016). The simultaneous utilization of agro-industrial residues further strengthens the circular character of the system by creating a localized material loop that reduces environmental pressure on both landfills and agricultural soils, a key characteristic of emerging decentralized circular models (Korhonen et al., 2018; Prendeville et al., 2018).

Despite these contributions, several limitations must be acknowledged. The evaluation focused solely on pH as an indicator of agronomic suitability and did not include plant-growth trials, nutrient-availability analysis, or long-term environmental assessment of hydrogel stability in soil. In addition, the laboratory-scale experimental setting does not fully capture



the variability of field conditions. These limitations indicate that the present findings should be interpreted as a proof of concept for circular planting-media development rather than as a complete agronomic validation.

Future research should extend the analysis to include plant-performance experiments, detailed physicochemical characterization of the planting media, and long-term monitoring of hydrogel behavior in soil ecosystems. Comparative studies involving different microbial inoculants, alternative organic residues, and varying fermentation durations would further refine the formulation design. In addition, life-cycle assessment and techno-economic analysis are necessary to evaluate the scalability, environmental benefits, and economic feasibility of implementing this circular bio-activation model at the household or community level, thereby supporting evidence-based circular-economy transitions (Hauschild et al., 2018).

In conclusion, this study demonstrates that diaper-derived hydrogel can be successfully integrated into planting media through LMO-based bio-activation while maintaining agronomically suitable pH conditions. The identification of an optimal hydrogel incorporation range provides a practical guideline for decentralized circular agriculture and community-based waste valorization. By transforming a persistent domestic waste into a regenerative input for plant cultivation, the proposed system contributes to the development of circular resource flows that simultaneously address waste management, sustainable agriculture, and local environmental resilience.

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