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Utilization of biogas spent slurry and agricultural waste for eco-friendly biodegradable nursery pots

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Abstract
The growing environmental burden of high-density polyethylene (HDPE) nursery bags and the disposal challenge of biogas spent slurry from Compressed Biogas (CBG) plants necessitate sustainable alternatives. This study explores the development of biodegradable nursery pots by valorizing biogas-digested slurry, including pressmud, municipal solid waste, and cow dung slurry, in combination with natural binders such as soil, lime, starch, and guar gum. A hydraulically operated compression molding machine was used to form the pots, which were evaluated for their physical, mechanical, and environmental properties. Results showed that pots formed with biogas slurry and guar gum exhibited superior performance, with compressive strength of 2.34 MPa, moisture content below 1%, shattering resistance of 86% and water absorption resistance under 30%. Biodegradability trials showed over 90% mass loss within 50-56 days under soil incubation. Germination tests confirmed that these pots supported healthy root development, achieving a 100% seed germination rate, surpassing that of HDPE controls. Electrical conductivity of pot leachate remained within safe limits, indicating no phytotoxic effects. The study demonstrates the feasibility of converting CBG slurry and agro-waste into structurally sound, biodegradable nursery pots, presenting a viable, eco-friendly substitute for plastic containers. The findings support sustainable nursery management, circular waste utilization, and align with national organic waste valorization initiatives.

Keywords: Biogas-spent slurry, Agricultural waste, Biodegradable nursery pots, Organic binders, Sustainable horticulture

1. Introduction

The intensification of horticultural practices and nursery production systems has led to widespread use of high-density polyethylene (HDPE) grow bags and plastic pots [1]. While these synthetic containers are cheap and convenient, their environmental persistence has emerged as a critical concern [2]. HDPE is non-biodegradable, photodegradable at best, and contributes to long-term soil and water pollution [3]. Moreover, the confined root growth in such containers often leads to spiraling and root deformation, reducing transplant success and overall plant health [4].

In parallel, the increasing push for renewable energy in India, particularly through the establishment of Compressed Biogas (CBG) plants under the SATAT and GOBARdhan missions, has resulted in the large-scale generation of digested biogas slurry as a by-product [5, 6]. As of 2024, India aimed to establish over 5,000 CBG plants with an annual target of 15 MMT of CBG production [7, 8]. The status of CBG plant density across India is shown in Fig. 1. This ambitious expansion has brought to the forefront a new environmental management challenge, the effective disposal and reuse of biogas spent slurry [9]. Although rich in organic matter and nutrients, improper disposal or over-application of digested slurry can pose risks of eutrophication, greenhouse gas emissions, and secondary pollution [10].

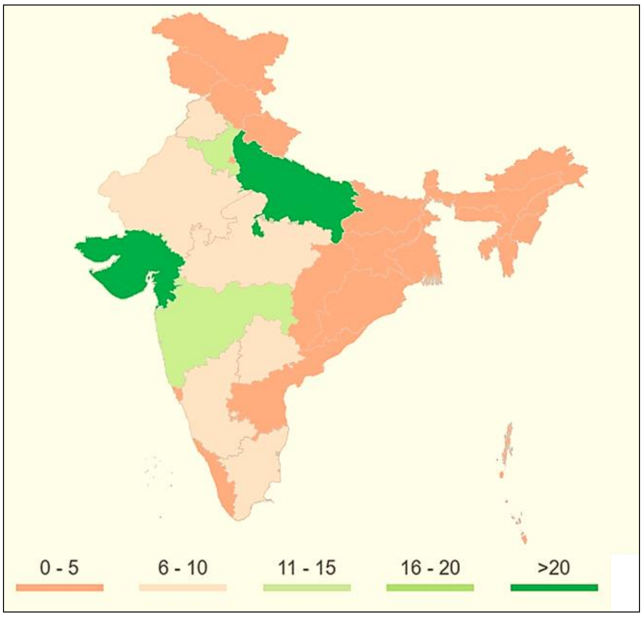

Fig 1: Status of CBG Plant density across India, March 2025

In this context, the concept of circular economy gains significant traction, wherein agricultural and agro-industrial wastes are reintegrated into value-added applications [11]. Several studies have proposed converting agro-waste into biodegradable packaging, soil conditioners, or bio-composites [12, 13]. Biogas spent slurry (BGS) was selected as the primary feedstock due to its unique physicochemical properties, including high organic carbon (~35-40%), fibrous structure, and balanced C:N ratio (20-25:1), which promote both mechanical stability and biodegradability [14]. Unlike other agro-wastes (e.g., rice husk or coconut coir), BGS's partial anaerobic digestion enhances lignin retention, critical for pot durability [15]. Among binders, guar gum was prioritized for its galactomannan polysaccharide structure, which forms hydrogels via hydrogen bonding, improving cohesion and moisture retention [16, 17]. Starch, though cost-effective, exhibits lower water resistance, while lime's exothermic reaction during curing accelerates shrinkage trade-offs. [18]. Furthermore, the potential to displace plastic containers in nurseries with such biodegradable alternatives aligns with global sustainability goals, including SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) [19].

Previous research has emphasized the role of organic binders such as starch, guar gum, and lime in enhancing the structural integrity of bio-composite products [17, 20]. These materials offer renewable, biodegradable, and often hydrophilic characteristics that improve pot durability and nutrient permeability [21, 22]. However, there exists limited literature that systematically evaluates the performance of biogas slurry-based nursery pots with various binder combinations under physical, mechanical, and environmental stress conditions [23].

This study aims to address the dual challenge of managing biogas slurry and reducing plastic pollution in nursery practices by developing an eco-friendly, biodegradable nursery pot using a blend of fermented organic manure (FOM) and agro-industrial residues. Specifically, the objectives of the study are to utilize biogas-digested slurry and agricultural waste as feedstock materials for pot formation. To incorporate soil, lime, starch, and guar gum as organic binders to enhance pot properties. Assess the physical (density, moisture, shrinkage), mechanical (compressive strength, shattering resistance), and environmental (water absorption, germination potential) performance of the developed bio-pots. Compare their performance with conventional plastic pots and explore their potential for large-scale nursery applications.

By transforming organic waste streams into biodegradable nursery containers, this study contributes to the development of a sustainable waste-to-wealth model. The results also offer practical implications for CBG plant operators, nursery managers, and policymakers in promoting integrated organic waste valorization strategies.

2. Materials and Methods

2.1 Raw Materials Collection and Preparation

Two major types of organic residues were used as base materials, such as biogas spent slurry and organic binders. The digested slurry, referred to as Fermented Organic Manure (FOM), was collected from operational Compressed Biogas (CBG) plants across different regions in India. The slurry was screened to remove oversized particles and sun-dried to reduce the initial moisture content to below 20%.

Pressmud, a fibrous by-product from sugarcane processing, and municipal solid waste (MSW) compost were collected from authorized composting sites. Both were pre-dried and sieved (<2 mm) to obtain uniform particulate matter for mixing. Cow dung slurry, partially digested under ambient anaerobic conditions, was procured from a local dairy unit and treated similarly.

The organic binders used in this study included clay soil (local loamy soil, sieved at 2 mm), Lime (CaO) for structural enhancement, Starch (industrial grade), and guar gum. All raw materials were stored in airtight containers under ambient conditions prior to mixing.

2.2 Feedstock and Binder Combinations

The primary feedstocks were tested in combination with four binders (soil, lime, starch, and guar gum). Feedstock-to-binder ratios (0.5:1 to 1.5:1) and compression pressures (100-300 bar) were tested in preliminary trials. A 1:1 ratio and 200 bar pressure were selected as optimal, ensuring structural integrity (compressive strength >1.5 MPa) without excessive brittleness. Therefore, the mixing ratio for each trial was maintained at 1:1 (w/w) between the organic base material and the binder. Water was added incrementally to obtain a workable consistency, with total moisture content adjusted to 35-40% (w.b.), suitable for compression molding. A total of 12 unique combinations were prepared and labeled for testing as presented in Table 1. The formulations were manually mixed using gloved hands and a stainless steel mixing basin to ensure uniform distribution of materials.

Table 1: Feedstock and binder combinations with proportions

Treatment No.	Treatment Code	Feedstock	Binder	Feedstock: Binder Ratio (w/w)
1	CD-S	Cow dung	Soil	1:1
2	CD-L	Cow dung	Lime	1:1
3	CD-IS	Cow dung	Starch	1:1
4	CD-GG	Cow dung	Guar Gum	1:1
5	PM-S	Press Mud	Soil	1:1
6	PM-L	Press Mud	Lime	1:1
7	PM-IS	Press Mud	Starch	1:1
8	PM-GG	Press Mud	Guar Gum	1:1
9	MSW-S	Municipal Solid Waste	Soil	1:1
10	MSW-L	Municipal Solid Waste	Lime	1:1
11	MSW-IS	Municipal Solid Waste	Starch	1:1
12	MSW-GG	Municipal Solid Waste	Guar Gum	1:1

2.3 Bio-Pot Formation Using Hydraulic Press
A semi-automatic, hydraulically operated bio-pot making machine was designed and fabricated for molding. The machine operated on a 3 HP, 3-phase hydraulic power-pack and included a hydraulic cylinder (100-400 kg/cm^2 capacity) connected to a mold and die assembly. The mold was made of HDPE with an inner diameter of 127 mm and a height of 127 mm, matching common nursery container dimensions.

The process included the following steps. Feed material was filled into the mold using a top-mounted manual hopper. The sliding assembly allowed accurate placement under the hydraulic piston. Compression was applied for a fixed duration of 2.5 seconds under 200 bar pressure, based on preliminary optimization trials. The pressed pot was ejected manually and transferred to drying trays. Each sample was shade dried for 48 hours to attain constant mass. The flow chart for the bio-pot production process is presented in Fig. 2.

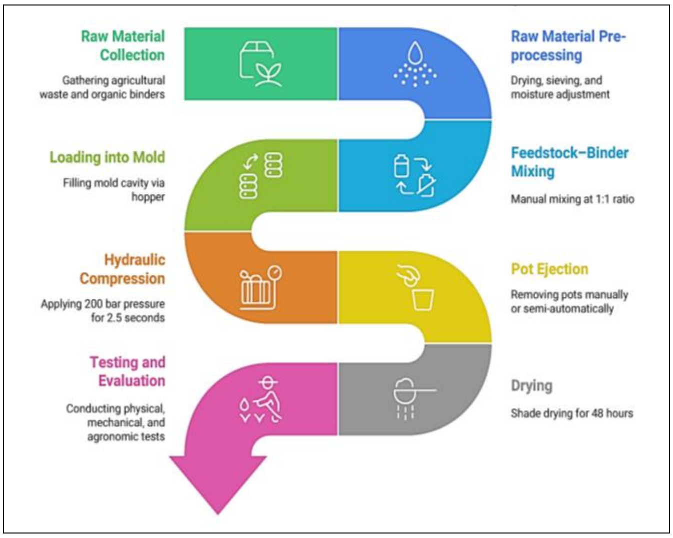

Fig 2: Flow chart of bio-pot production process

2.4 Testing of Bio-Pot Properties
All formed pots were subjected to a series of physical, mechanical, and environmental tests as per relevant ASTM and BIS standards [24].

2.4.1 Physical Properties
2.4.1.1 Moisture content
Moisture content represents the amount of water retained in the bio-pot samples and significantly influences their drying behavior and mechanical stability. It was determined using the oven-dry method, where samples were dried at 105 °C for 24 hours as per ASTM D2216. Lower moisture content indicates better drying efficiency and structural integrity. The moisture content in bio-pots was determined as;

$$\text{Moisture Content (MC,\%)} = \frac{W_1 - W_2}{W_1} \times 100 \qquad \ldots(1)$$

Where,
W_1 = Initial weight of the sample (g)
W_2 = Oven-dry weight of the sample (g)

2.4.1.2 Density
Density is a key physical property that reflects the compactness and mass distribution within the bio-pot structure. It was calculated by measuring the dry weight of each sample and dividing it by its total volume, providing insights into material compaction and strength. Higher density generally correlates with better mechanical performance. The density of the bio-pots was evaluated using the formula;

$$\text{Density (kg/m}^3) = \frac{\text{mass (m)}}{\text{Volume (V)}} \qquad \ldots(2)$$

2.4.1.3 Shrinkage
Shrinkage indicates the dimensional reduction of the bio-pot during the drying process, which affects its shape stability and usability. It was calculated by measuring the difference between the initial mold dimensions and the final dried dimensions, expressed as a percentage. Excessive shrinkage may lead to deformation or cracking in the pots. Shrinkage in the bio-pots was calculated using the formula;

$$\text{Diameter Shrinkage (D,\%)} = \frac{D_1 - D_2}{D_1} \times 100 \qquad \ldots(3)$$

Where,
D_1 and D_2 = initial and final diameter (mm)

2.4.2 Mechanical Properties
2.4.2.1 Compressive strength
Compressive strength reflects the load-bearing capacity of the bio-pots, essential for handling and stacking during nursery operations. It was evaluated using a Universal Testing Machine (UTM) at a constant loading rate of 5 mm/min, following ASTM D695. Higher compressive strength indicates better mechanical durability and resistance to deformation under stress. The compressive strength was computed as,

$$\text{Compressive strength (MPa)} = \frac{F_{max}}{A} \qquad \ldots(4)$$

Where,
F_{max} = Maximum load at failure (N)
A = Load-bearing surface area (mm^2)

2.4.2.2 Shattering resistance
Shattering resistance assesses the bio-pot's ability to withstand impact during handling and transportation. It was tested by performing a drop test from a height of 1.83 m onto a concrete floor, as per ASTM D3038-93. The survival rate (%) was calculated based on the number of samples that remained intact after impact. The shattering strength of bio-pots was calculated as,

$$\text{\% weight loss} = \frac{W_1 - W_2}{W_1} \times 100 \qquad \ldots(5)$$

$$\text{\% shattering resistance} = 100 - \text{\% weight loss} \qquad \ldots(6)$$

Where,
W_1 = mass of bio-pot sample before shattering (g)
W_2 = mass of bio-pot sample after shattering (g)

2.4.3 Environmental Properties
2.4.3.1 Water absorption resistance
Water absorption resistance indicates the extent to which bio-pots can resist moisture when exposed to wet conditions, which affects their durability and biodegradability. It was determined by immersing the dried samples in distilled water for 4 hours and calculating the percentage increase in weight, representing the amount of water absorbed and determined as,

$$\text{\% water gained by bio-pots} = \frac{W_1 - W_2}{W_1} \times 100 \qquad \ldots(7)$$

% water absorption resistance = 100 -% water gained …(8)

Where,
W_1 = mass of bio-pots sample before test (g)
W_2 = mass of bio-pots sample after test (g)

2.4.3.2 Biodegradability

Biodegradability reflects the environmental sustainability of the bio-pots by measuring their decomposition over time. It was assessed over 90 days by burying the pots in moist soil-filled trays maintained under controlled greenhouse conditions. Degradation was monitored both visually and by calculating the percentage of mass loss at regular intervals.

$$\text{Biodegradation (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad \ldots(9)$$

Where,
W_1 = Initial dry weight (g)
W_2 = Dry weight after days (g)

2.4.4 Electrical Conductivity

Electrical conductivity (EC) indicates the potential release of soluble salts from bio-pot materials into the surrounding environment during degradation. To assess this, samples were immersed in distilled water, and the resulting solutions were analyzed using a digital EC meter. Higher EC values suggest greater ionic leaching, which may influence soil chemistry and seedling health.

3. Results and Discussion

The results of physical, mechanical and environmental analysis of bio-pots are presented in Table 2.

Table 2: Properties of bio-pots

Treatment No.	Moisture Content (%)	Bulk Density (kg/m³)	Shrinkage (%)	Compressive Strength (MPa)	Shattering Resistance (%)	Water Absorption (%)	Electrical Conductivity (dS/m)
1.	0.52	1166.60	10.00	0.55	55.56	22.22	1.05
2.	0.45	1192.52	10.00	0.58	58.70	21.74	1.12
3.	0.64	1125.12	5.00	0.58	67.97	20.28	0.94
4.	0.92	1044.57	14.00	0.83	86.29	28.57	0.89
5.	0.39	1270.30	10.00	0.40	38.78	9.18	1.18
6.	0.23	1068.09	8.00	0.56	51.46	10.68	1.31
7.	0.28	1036.98	5.00	0.54	62.50	7.50	1.10
8.	0.27	1048.83	15.00	1.04	73.54	14.81	1.53
9.	0.21	1251.32	9.00	0.61	42.55	15.96	1.52
10.	0.37	1062.90	7.00	0.51	51.22	9.76	1.43
11.	0.28	969.11	10.00	0.55	68.68	15.93	1.25
12.	0.22	1158.75	18.00	2.34	75.00	12.50	1.12

3.1 Physical Characteristics of the Bio-Pots

The physical integrity of the molded bio-pots is a critical determinant of their handling, transportation, and nursery performance. Among the combinations tested, pots formed using FOM and guar gum exhibited the most uniform surface texture and minimal dimensional warping, indicating good moldability and adhesion during pressing. The measured moisture content of the dried bio-pots ranged from 0.2 - 0.9%, with lower values associated with starch and guar gum-bound formulations. These low moisture levels, achieved after oven drying, are essential for long-term storage and structural stability. The variation in moisture can be attributed to the differing hygroscopic properties of the binders used. Guar gum, a *galactomannan polysaccharide*, demonstrated better moisture regulation, likely due to its ability to form a stable gel matrix within the organic matrix [25].

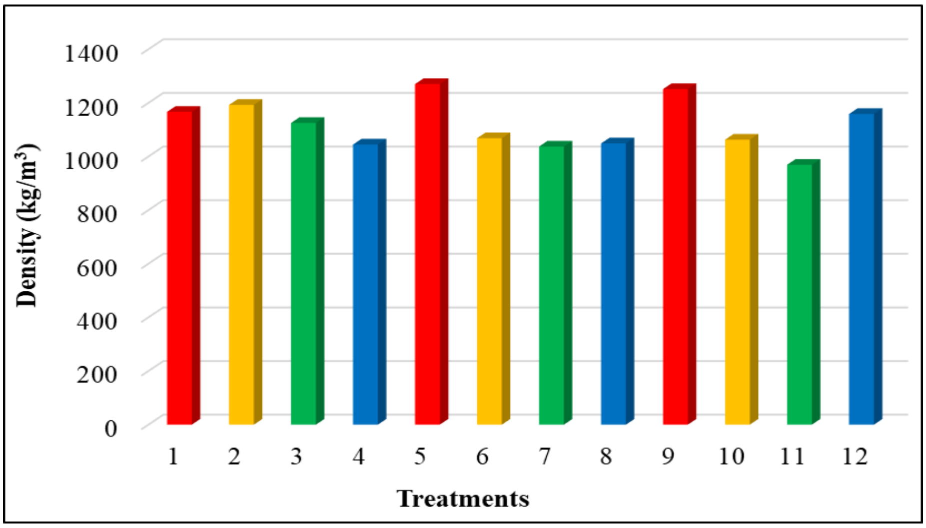

Fig 3: Density of developed bio-pots

The density of the bio-pots varied from 960 to 1270 kg/m³, with the densest samples recorded in lime-based combinations as presented in Fig. 3. Higher density indicates greater compaction and reduced pore volume, which may affect water drainage and aeration. Nevertheless, moderate density is desirable to ensure sufficient strength without compromising root permeability.

Shrinkage analysis showed that most formulations underwent 5% to 18% linear contraction during drying, predominantly along the height axis. This shrinkage is attributable to water evaporation and binder polymerization. Notably, pots containing lime exhibited higher shrinkage, possibly due to increased binding and water loss, whereas those with starch showed more dimensional stability.

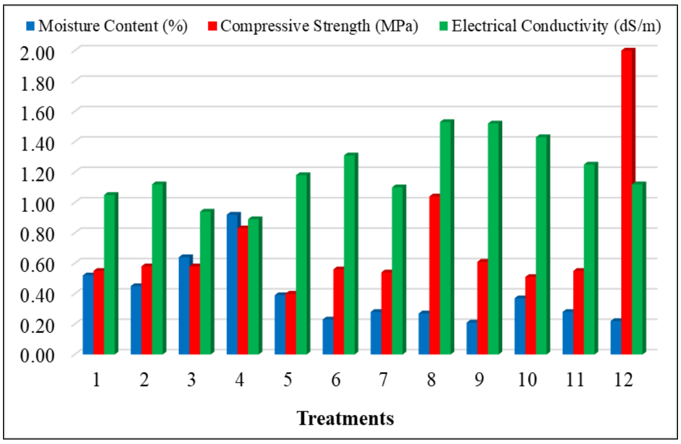

Fig 4: Moisture content, compressive strength and electrical conductivity of bio-pots

3.2 Mechanical Strength and Durability Assessment

Mechanical performance is paramount for any container intended for handling, stacking, and transplanting operations. Compressive strength values ranged from 0.4 MPa to 2.34 MPa, with the highest values recorded for FOM + guar gum combinations as presented in Fig. 4. These strengths are within acceptable limits for horticultural containers and suggest that bio-pots can withstand nursery handling operations without mechanical failure. The higher strength in guar gum-bound samples may be linked to improved internal cohesion and uniform stress distribution, as observed in other natural polymer matrices [26].

Shattering resistance, measured through a standardized drop test, demonstrated the resilience of the pots to sudden impact. While some formulations (notably MSW + soil) suffered up to 40% failure rate upon repeated drops, pots containing starch and guar gum showed greater resilience with survival rates above 85%. This indicates that natural polysaccharide binders can improve shock absorption properties and fracture toughness by enhancing inter-particle adhesion.

3.3 Water Resistance and Moisture Interaction

Water absorption capacity, a critical parameter affecting pot stability during irrigation, ranged from 18.6% to 38.2% after 4 hours of immersion. Combinations involving starch and guar gum exhibited lower water uptake, suggesting superior water resistance. In contrast, soil-bound formulations absorbed significantly more moisture, which can lead to premature disintegration. Excessive water absorption can compromise mechanical strength, accelerate microbial degradation, and hinder pot functionality in humid conditions. These findings underscore the importance of binder selection in determining pot performance in real-world nursery environments.

The electrical conductivity (EC) of pot leachates, used as a proxy for nutrient release and salt buildup potential, ranged from 0.68 to 1.52 dS/m. All values remained within the acceptable range for seedling growth, although slightly elevated EC levels were observed in formulations using pressmud due to its inherent mineral content. The moderate conductivity of the FOM-based pots indicates gradual nutrient leaching, which can benefit young seedlings during early growth phases without inducing osmotic stress.

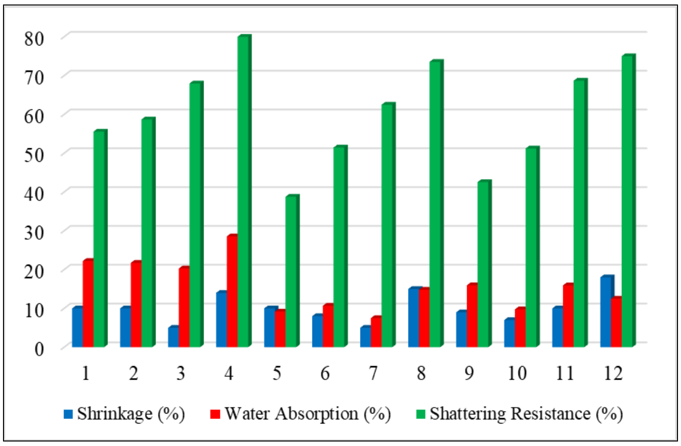

Fig 5: Shrinkage, water absorption and shattering resistance of bio-pots

FOM+guar gum pots demonstrated significantly higher compressive strength (2.34 ± 0.12 MPa) compared to soil-bound (0.55 ± 0.08 MPa) and starch-bound (0.58 ± 0.10 MPa) formulations. This aligns with guar gum's ability to form a cross-linked hydrogel matrix, reducing pore space and enhancing stress distribution. Conversely, lime-bound pots showed 15-18% higher shrinkage (Fig. 5), attributed to rapid moisture loss during CaO hydration. Shattering resistance correlated strongly with binder type, with guar gum's elastic modulus (~1.2 GPa) mitigating fracture propagation.

3.4 Biodegradability and Environmental Compatibility

The biodegradation profile of the bio-pots was monitored over a 90-day soil incubation period. Pots made from CD, MSW and PM exhibited visible softening and partial breakdown by day 45, with complete disintegration observed in most combinations by day 50 as illustrated in Fig.6. Mass loss data corroborated visual assessments, showing 60-95% reduction in dry weight, depending on the binder and feedstock. Guar gum and starch combinations degraded more uniformly and rapidly compared to lime or soil, which likely persisted longer due to lower microbial accessibility. These findings affirm the biodegradability of the bio-pots and their compatibility with natural soil ecosystems.

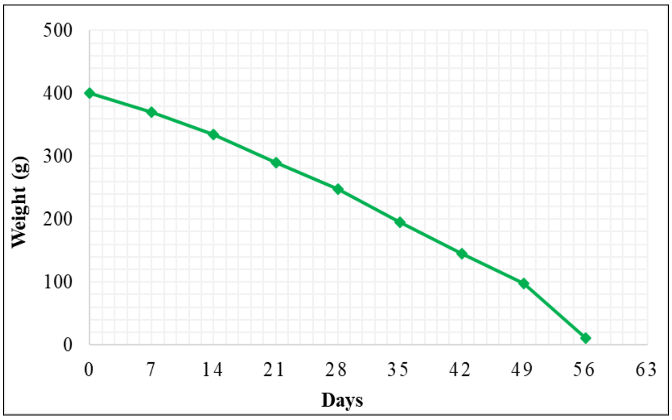

Fig 6: Biodegradation of press mud bio-pots

Importantly, no toxic residues or harmful odors were noted during degradation, indicating that the materials used are safe for soil health. The presence of humified organic matter post-degradation also suggests potential soil enrichment, further contributing to a circular nutrient economy. The rapid and complete degradation observed in most formulations aligns with previous studies that demonstrated enhanced microbial activity in organic matrix systems [27].

3.5 Comparison with Conventional Plastic Nursery Pots

When compared to conventional HDPE nursery pots, the developed bio-pots demonstrate multiple environmental and agronomic advantages. While plastic pots are durable and water-resistant, they are non-biodegradable and contribute to long-term environmental pollution. The performance of bio-pots in terms of compressive strength and durability approaches that of plastic containers, but with the added benefits of biodegradability and soil enrichment.

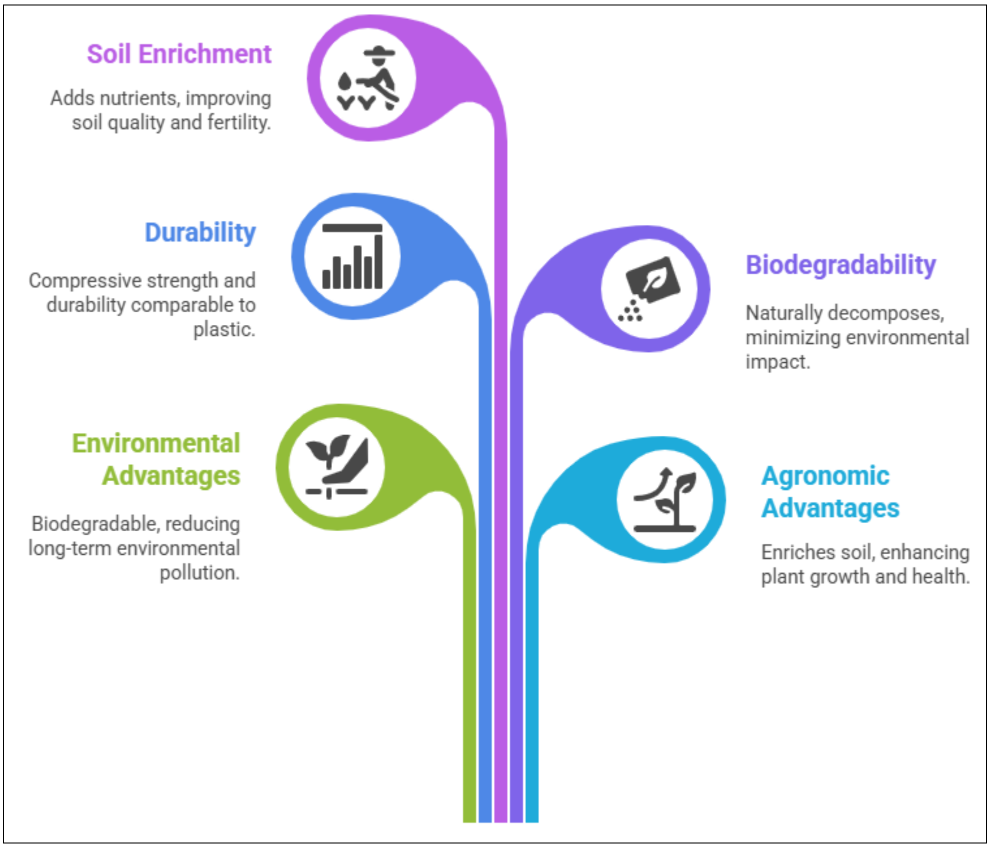

Fig. 7: Agronomic advantages of bio-pots

Moreover, HDPE containers can induce root spiraling due to constrained aeration and poor drainage, whereas bio-pots constructed from porous organic matrices encourage natural root growth and avoid deformation. The cost of production per pot, as determined through economic analysis, remains competitive (~₹28.69 per pot), especially when raw materials are sourced from local waste streams. These findings support the feasibility of replacing plastic grow bags with biodegradable alternatives in nursery practices.

4. Conclusion

This study successfully demonstrated the potential of utilizing biogas spent slurry combined with agricultural residues and organic binders to produce eco-friendly, biodegradable nursery pots. The optimized hydraulic compression molding process effectively transformed these waste materials into structurally stable pots, with the combination of fermented organic manure and guar gum exhibiting superior physical and mechanical properties. The developed bio-pots showed adequate compressive strength, water resistance, and low shrinkage, making them suitable for nursery applications.

Importantly, the bio-pots exhibited rapid and complete biodegradability within 56 days under soil conditions without releasing phytotoxic substances, thereby ensuring environmental safety. Germination trials confirmed that the bio-pots not only support healthy seedling growth but also offer advantages over conventional plastic pots by enabling root penetration and reducing transplant shock. Overall, this research presents a sustainable waste-to-wealth approach that addresses critical environmental challenges: the disposal of biogas slurry and the proliferation of plastic waste in horticulture. Adoption of these biodegradable bio-pots can contribute significantly to sustainable nursery practices, promote circular economy principles, and reduce reliance on non-degradable plastics. Further studies focusing on large-scale production and life cycle assessment are recommended to facilitate commercialization and broader environmental impact assessment.

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Conflict of Interest

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.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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