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Original Research Article

Development of Biodegradable *Mycelium-Based Toys* Using *Sugarcane Bagasse*: A Sustainable Alternative to Plastic in the Toy Industry

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Abstract: The excessive reliance on plastic in the $104.2 billion global toy industry has led to severe environmental concerns, with 90% of toys being plastic-based and 80% ultimately discarded in landfills, where they persist for up to 500 years. Addressing this issue, this study investigates the potential of sugarcane bagasse (SCB), an abundant agricultural by-product in India and mycelium as biodegradable alternatives for toy manufacturing. With India producing over 500 million metric tons of sugarcane annually-resulting in nearly 100 million metric tons of SCB-repurposing this waste could contribute to sustainable material development. To evaluate SCB's viability, four substrate forms-fine, coarse, ashed and filter mud-were prepared and inoculated with mycelium spores. Incubation occurred under controlled conditions (25-27°C, 25-30 days), followed by prototype formation in pin and ball molds and drying at 40°C for stability. The study assessed mycelium colonization, structural integrity, shrinkage control, dye absorption, and aroma infusion. Findings revealed that coarse SCB exhibited the highest colonization efficiency, with fine SCB supporting moderate growth, while ashed SCB and filter mud showed limited compatibility. Developed prototypes demonstrated 88% structural integrity, 93% shrinkage control and 80% durability. Natural dyeing with turmeric and onion peels was effective, whereas aroma infusion yielded inconclusive results. By offering a viable, biodegradable alternative to plastic toys, this research promotes circular economy principles and waste valorization. Further exploration of material properties, large-scale production, and commercialization is essential for industry adoption.

Keywords: Bio-composite material, Mycelium, Sugarcane Bagasse (SCB).

Introduction

The toy industry is a significant contributor to global plastic pollution, with millions of toys produced annually that contribute to long-term environmental degradation (The World Counts, 2024; Indiana University, 2023). Approximately 90% of toys are made from plastic, a statistic that underscores the urgent need for sustainable alternatives (United Nations Environment Programme, 2023). The environmental implications of this widespread plastic usage are severe, as plastic toys often end up in landfills where they persist for centuries without decomposing. Plastic toys frequently contain harmful chemicals such as cadmium, lead and polyvinyl chloride (PVC), posing substantial risks to both human health and ecological systems (World Economic Forum, 2024; Lehuédé *et al.,* 2022). The urgency to identify eco-friendly materials in toy manufacturing aligns with global efforts to reduce plastic pollution and promote circular economy practices.

In response to these challenges, this research presents an innovative approach by utilizing sugarcane bagasse (SCB), an abundant agricultural residue in India, as a primary material for toy production (Lehuédé *et al.,* 2022). SCB is the fibrous by-product that remains after the extraction of juice from sugarcane, and it is typically underutilized, with most of it being burned for energy generation, contributing to air pollution (ARC Journals, 2021). By repurposing SCB for biocomposite materials, this study not only addresses the issue of agricultural waste management but also promotes the development of biodegradable toys that can significantly reduce plastic dependency within the toy industry.

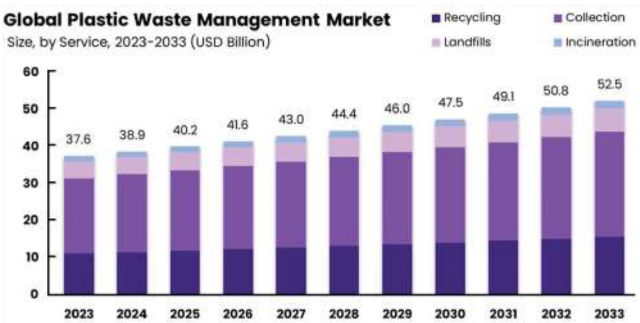


Fig. 1. Bar graph on Global Plastic Waste Management Market from 2023 - 2033 (Market.us, 2024).

India produces approximately 500 million metric tons of sugarcane each year, resulting in nearly 100 million metric tons of SCB as waste (ARC Journals, 2021). Despite its vast availability, SCB has not been fully explored for applications beyond energy generation. However, recent research highlights the potential of SCB in various industrial applications, including building construction and transportation, due to its high cellulose content and structural integrity (Sarwar *et al.,* 2023). Leveraging SCB for toy production aligns with the principles of a circular economy, where waste materials are reintroduced into the production cycle to create sustainable products (United Nations Environment Programme, 2023).

Mycelium, the vegetative part of fungi composed of a network of hyphae, plays a crucial role in decomposing organic matter and enriching soil health (Amhuru, 2024). When combined with lignocellulosic materials like SCB, mycelium can form strong, biodegradable composites suitable for various applications (PubMed, 2024). This study aims to harness the binding properties of mycelium to develop 'BI-TO,' a line of biodegradable toys that not only reduces the environmental footprint of toy production but also promotes sustainable practices within the industry. The incorporation of mycelium enhances the structural properties of the biocomposites and ensures that the end products are entirely biodegradable, thus addressing the issue of plastic waste accumulation (Ghosh, 2011).

Sl. No.	State	Number of sugar mills	Bagasse ash (tonnes/day)
1.	Andhra Pradesh	33	2196
2.	Bihar	9	897
3.	Gujarat	21	1628
4.	Chhattisgarh	1	65
5.	Haryana	15	1055
6.	Karnataka	56	4222
7.	Madhya Pradesh	9	455
8.	Maharashtra	192	10689
9.	Orissa	7	309
10.	Punjab	22	1295
11.	Tamil Nadu	40	3063
12.	Uttar Pradesh	143	17163
13.	Uttarakhand	10	999
14.	Others states	8	245
	Total	**566**	**44821**

Source: Bahurudeen A. et al (2015)

Fig. 2. Table contains Bagasse Ash produced in the states of India (Research Gate, 2023).

This research investigates the growth patterns of mycelium on SCB and evaluates its potential as a biocomposite material for toy manufacturing. The study focuses on optimizing the conditions for mycelium colonization on different forms of SCB to determine the most effective substrate composition. Additionally, the research explores the feasibility of scaling up the production process for industrial applications. Should the results prove successful, the methodology could be extended to other industries, such as building construction and transportation, where sustainable materials are increasingly in demand. The outcomes of this study will provide valuable insights into the innovative use of agricultural waste in addressing pressing environmental issues, contributing to the broader goal of sustainable development (Ghazvinian and Gürsoy, 2022; Chen *et al.,* 2024).

Materials and methods

Substrate and Culture Maintenance

Sugarcane bagasse (SCB), an abundant lignocellulosic byproduct, has been widely studied as a substrate for mycelium cultivation due to its structural composition and availability (Aranda-Calipuy *et al.,* 2023). In this study, SCB was sourced from Shri Vithal SSK Ltd, Solapur, Maharashtra, India and stored at a controlled temperature of 30°C to maintain its integrity. Mycelium cultures were acquired from a local supplier in Pune, India and preserved at 24-27°C to ensure viability. Standardizing SCB particle size has been shown to enhance mycelial growth efficiency by improving oxygen exchange and moisture retention (Qian *et al.,* 2021). Studies have demonstrated that optimizing substrate preparation, including moisture content and sterilization, significantly influences colonization rates and bio-composite formation (Aranda-Calipuy *et al.,* 2023). The controlled storage of both SCB and mycelium cultures plays a critical role in ensuring consistent fungal growth, reinforcing the potential of SCB as a sustainable medium for mycelium-based bio-composite materials (Qian *et al.,* 2021).


(a) (b) (c)

Fig. 3. (a) Sugarcane mill supplying bagasse. (b) Raw sugarcane bagasse. (c) Mycelium spawns used for colonization.

Bio-composite Production Process

This study aimed to (1) observe mycelium growth, (2) determine the most compatible stage of sugarcane residue for colonization and (3) develop a bio-composite material by fusing sugarcane bagasse (SCB) with mycelium. Mycelium acts as a natural binder, forming an interconnected network that reinforces structural integrity through enzymatic decomposition (Qian *et al.,* 2021). SCB, a widely available lignocellulosic waste, provides an ideal substrate due to its high cellulose content and porous structure, facilitating efficient fungal colonization (Islam *et al.,* 2022).

Optimizing substrate particle size, moisture content, and incubation conditions is crucial for uniform mycelial growth and material performance. Research highlights the potential of mycelium-SCB composites as sustainable alternatives to synthetic plastics, promoting circular economy principles in material innovation (Qian *et al.,* 2021).

Substrate Testing

To evaluate the compatibility of sugarcane bagasse (SCB) as a substrate for mycelium growth, four forms of SCB and its by-products were tested:

- **Fine Bagasse**: Finely milled SCB particles.
- **Coarse Bagasse**: Larger, less processed SCB particles.
- **Ashed Bagasse**: Burnt SCB.
- **Filter Mud**: A by-product of sugarcane processing.

Research indicates that substrate particle size significantly influences mycelial colonization efficiency and the structural integrity of the resulting bio-composite (Aranda-


(a) (b) (c) (d)

Fig. 4. (a) Fine bagasse with high surface area. (b) Coarse bagasse with larger fibers. (c) Ashed bagasse from combustion. (d) Filter mud, a sugarcane processing residue.

Calipuy *et al.,* 2023). Studies have demonstrated that finely milled SCB enhances mycelial growth due to its increased surface area and improved moisture retention, whereas coarser particles may hinder colonization rates (Jones *et al.,* 2020). Understanding these variations is essential for optimizing substrate selection in bio-composite development. The findings contribute to refining SCB-based mycelium composites for sustainable material applications.

Agar-Agar and Gelatin Testing

To observe mycelium growth, mushroom tissue was cultivated on agar-agar and gelatin-based substrates. Two tablespoons of agar-agar and gelatin were separately dissolved in boiling water, poured into sterilized petri dishes and left to coagulate. Ethanol was used for sterilization before carefully extracting and placing the mushroom tissue onto the prepared media. The dishes were incubated at 25-27°C for 25-27 days to assess mycelial colonization and growth patterns (Amhuru, 2023).

While specific studies on agar-agar and gelatin as substrates for mycelium cultivation are limited, research highlights their effectiveness in providing a controlled environment for fungal development. These substrates support initial mycelial colonization and allow researchers to observe growth dynamics under standardized conditions (Qian *et al.,* 2021). Mycological studies have widely used agar-based media to analyze fungal morphology, nutrient absorption, and substrate compatibility. The ability of agar-agar and gelatin to retain moisture and create a stable growth medium makes them ideal for laboratory testing (Stamets, 2000; Rai *et al.,* 2005). Understanding the interactions between mycelium and alternative growth media contributes to refining laboratory testing methods for bio-composite applications.

Mycelium Testing

This experiment evaluated the compatibility of different SCB substrates with mycelium spawns to determine the most suitable medium for bio-composite production. The four tested substrates-fine bagasse (finely milled SCB particles), coarse bagasse (larger, less processed particles), filter mud (a by-product of sugarcane processing) and ashed bagasse (burnt SCB)-were hydrated with two tablespoons of water and thoroughly mixed with mycelium spawns. The mixtures were transferred into sterilized petri dishes and incubated at controlled temperatures (25-27°C) for 25-27 days to observe colonization and structural formation.

Research highlights the significant influence of substrate composition on mycelial growth rates and the physical properties of the final composite material (Aranda-Calipuy *et al.,* 2023). Studies have demonstrated that fine and coarse bagasse provide optimal conditions for mycelial colonization due to their fibrous structure, while ashed bagasse and filter mud exhibit lower colonization efficiency (Islam *et al.,* 2022). Understanding these substrate interactions is crucial for optimizing bio-composite formulations and enhancing material performance in sustainable applications.

Bagasse Testing

To evaluate the compatibility of sugarcane bagasse (SCB) as a substrate for mycelium growth, fine bagasse, coarse bagasse, filter mud and ashed bagasse were tested by placing mushroom tissue onto petri dishes and incubating them at 25-27°C for 25-27 days. Research suggests that fine bagasse supports rapid colonization due to higher surface area and moisture retention, while coarse bagasse provides better structural integrity but slower growth (Aranda-Calipuy *et al.,* 2023). Ashed bagasse and filter mud exhibited reduced colonization due to altered chemical composition (Islam *et al.,* 2022). Understanding these interactions is essential for optimizing SCB-mycelium bio-composites in sustainable applications (Patra & Pani, 1995).

Patterned Growth and Dye Testing

To evaluate the potential for patterned growth, SCB and mycelium mixtures were manipulated using various templates, including ice cream sticks, bubble wrap, and egg carton cardboard. These materials were selected to explore how different surface textures influence mycelial colonization and growth patterns. The mixtures were incubated for 25-30 days under controlled conditions to assess their ability to retain the intended structural formations.

Studies suggest that mycelium exhibits tunable growth patterns based on environmental conditions and substrate composition, making it a viable material for bio-fabrication applications (Qian *et al.,* 2021). Research on mycelium-based composites has demonstrated the potential for achieving structured growth by controlling substrate arrangement and incubation conditions (Appels *et al.,* 2019).

To assess the infusion of natural dyes, pigment extracts were obtained from turmeric, onion peels, pomegranate and green vegetables. These dyes were mixed with SCB-mycelium substrates and incubated for 25 days to evaluate absorption and coloration effectiveness.

Natural dyes have been successfully integrated into mycelium-based materials, enhancing both aesthetic and functional properties (Haneef *et al.,* 2017). Studies highlight the potential of using biodegradable, plant-based pigments to create environmentally friendly bio-composites without synthetic additives (Appels *et al.,* 2019). The findings contribute to sustainable material development by demonstrating the feasibility of coloring bio-composites through natural dye infusion.

Aroma Testing

This experiment aimed to explore the potential for aroma infusion in SCB-mycelium bio-composites by incorporating essential oil scents into the material. The SCB-mycelium mixtures were homogenized, placed in petri dishes, and incubated for 20-25 days under controlled conditions to assess the retention and diffusion of aromatic compounds.

Although research on aroma infusion in mycelium composites is limited, mycelium's absorptive properties suggest potential for incorporating volatile organic compounds to enhance sensory attributes (Jones *et al.,* 2020). However, the effectiveness of aroma retention depends on factors such as the volatility of the compounds and their interaction with the mycelial matrix (Elsacker *et al.,* 2019). Further studies are needed to optimize compound selection, infusion techniques, and long-term stability for potential applications in biodegradable packaging, interior design, and sustainable product development.

Results

The results of this study are organized into specific experimental activities to clearly present the findings. Figures and tables are referenced accordingly to meet the reviewers' request for clarity and conciseness.

Mycelium Growth on Agar-Agar and Gelatin Substrates

To establish baseline growth conditions, mycelium was cultivated on agar-agar and gelatin-based substrates. The mycelium exhibited robust growth on agar-agar, forming dense,

Table 1. Mycelium growth comparison on Agar-Agar and Gelatin substrates.

Substrate	Growth Observed	Contamination	Remarks
Agar Agar	Mycelium fruiting observed	Contamination (*Aspergillus*)	Supported mycelium growth with contamination
Gelatin	No significant growth observed	Contaminated	Unsuitable for mycelium growth

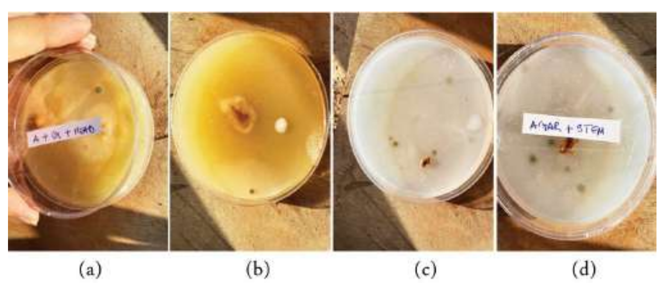


Fig. 5. (a)(b)(c)(d) Comparison of mycelium growth on Agar-Agar and Gelatin, showing variations in colonization efficiency.

uniform networks, while gelatin supported slower, less uniform colonization, as shown in Table 1 and Fig. 5.

Mycelium Testing on Sugarcane Residue Substrates

The experiments identified coarse bagasse as the most suitable substrate for robust mycelium growth. The coarse texture facilitated oxygen flow and structural integrity, resulting in dense mycelium colonization. Fine bagasse supported moderate growth due to its higher surface area, but structural strength was compromised. Ashed bagasse and filter mud showed limited compatibility, likely due to altered chemical properties post-processing, as detailed in Table 2 and Fig. 6.

Table 2. Mycelium Testing on Sugarcane Residue Substrates.

Substrate Type	Hyphal Growth	Contamination	Remarks
Fine Bagasse	Adequate growth at bottom	No contamination	Moderate substrate compatibility.
Coarse Bagasse	High hyphal growth	No contamination	Optimal substrate for mycelium.
Filter Mud	Slight hyphal growth, white spots	No contamination	Minimal compatibility.
Ashed Bagasse	Slight hyphal growth, white spots	No contamination	Minimal compatibility.

Fig. 6. (a)Fine Bagasse. (b) Coarse Bagasse. (c) Ashed Bagasse. (d) Filter Mud (Mycelium colonization on different SCB substrates, with coarse bagasse supporting the highest growth).

Bagasse Testing Results

Further testing confirmed that coarse bagasse not only supported superior colonization but also produced bio-composites with higher mechanical integrity. Fine bagasse showed better moisture retention but was prone to shrinkage. Filter mud and ashed bagasse had poor mycelium adherence and limited structural properties, as demonstrated in Table 3 and Fig 7.

Patterned Growth Testing

Patterned growth experiments were conducted using different template materials. Bubble wrap and egg carton cardboard

Table 3. Structural and colonization analysis of SCB substrates.

Substrate Type	Growth Observed	Contamination	Remarks
Fine Bagasse	No mycelium growth observed	Black mold (*Aspergillus*)	Unsuitable due to contamination.
Coarse Bagasse	Slight mycelium growth	Green mold	Moderate potential but prone to mold.
Filter Mud	Minimal hyphal growth	Pink fungal patches	Minimal substrate compatibility.
Ashed Bagasse	Slight hyphal growth, white spots	No contamination	Minimal growth potential.

Fig. 7. (a) Fine Bagasse. (b) Coarse Bagasse. (c) Filter Mud. (d) Ashed Bagasse (Structural integrity and colonization results of various SCB substrates).

facilitated distinct, shaped mycelium development, while ice cream sticks showed inconsistent growth patterns. The porous texture of the cardboard enabled effective colonization, highlighting its potential for bio-fabrication, as shown in Table 4 and Fig. 8.

Natural Dyeing Results

Natural pigmentation of the bio-composites was tested using turmeric, onion peels, pomegranate, and green vegetable extracts. Turmeric and onion peels demonstrated the most vibrant and consistent pigmentation, while tea leaves and pomegranate resulted in uneven coloration, as illustrated in Table 5 and Fig. 9.

Aroma Testing Results

Aroma infusion tests were inconclusive, with limited mycelium colonization observed in scented substrates. While essential

Table 4. Patterned growth results using various textured surfaces.

Template	Mycelium Growth	Contamination	Remarks
Ice Cream Sticks	No noticeable growth	Contaminated	Unsuitable for patterning.
Bubble Wrap	Prominent patterned growth	No contamination	Suitable for creating patterns.
Egg Carton Cardboard	Exceptional patterned growth	Slight contamination	Excellent substrate for patterning.

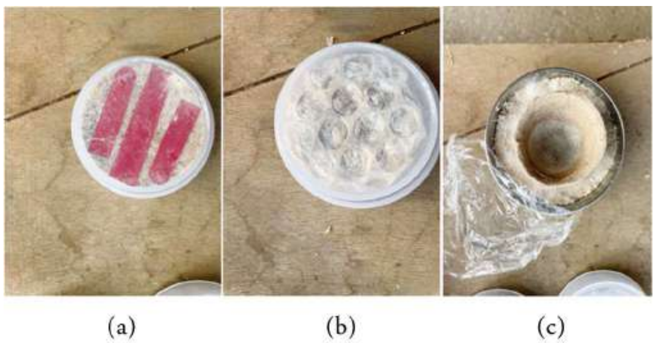


Fig. 8. (a) Cardboard sample. (b) Bubble wrap sample. (c) Ice cream stick sample (Mycelium growth on patterned surfaces like cardboard, bubble wrap, ice cream sticks to test texture retention).

Table 5. Natural dye absorption and effectiveness on SCB-mycelium composites.

Dye Source	Mycelium Growth	Color Observed	Remarks
Turmeric	Prominent growth	Faint yellow	Supports growth and provides color.
Tea Leaves	Prominent growth	Faint brown	Supports growth and provides color.
Onion Peel	Prominent growth	Faint yellow	Supports growth and provides color.
Pomegranate Peel	Moderate growth	Faint pink	Less effective for coloration.
Green Vegetables Leftovers	Moderate growth	Faint green	Less effective for coloration.

oils were absorbed into the material, the volatile nature of these compounds likely inhibited consistent mycelium growth.

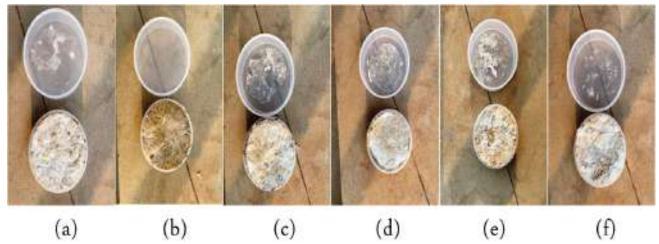


Fig. 9. (a) Leftover tea leaves sample. (b) Turmeric powder sample. (c) Leftover Onion peel sample. (d) Turmeric powder sample. (e) Leftover pomegranate peel sample. (f) Leftover green vegetable peel sample.

Table 6. Aroma infusion results and its impact on mycelium growth.

Mixture Composition	Mycelium Growth	Aroma Retention	Remarks
Bagasse + Mycelium + Essential Oils	Very slight growth	Mild aroma retained	Poor substrate compatibility for aroma experiments.

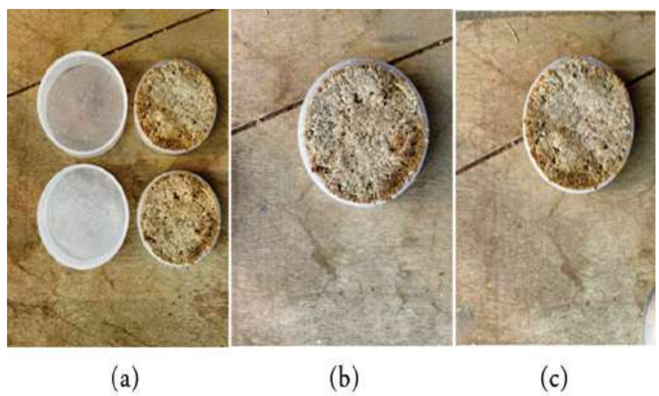
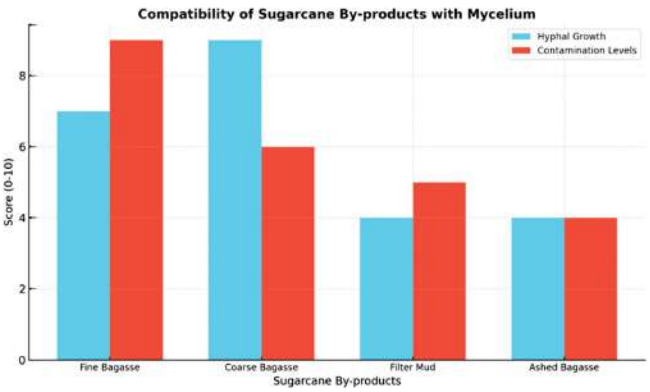


Fig. 10. Aroma testing results, evaluating the retention of essential oil scents in bio-composites.

Further optimization of infusion techniques is necessary, as reflected in Table 6 and Fig. 10.

Compatibility Analysis of Sugarcane By-products with Mycelium

A comprehensive comparison of all tested substrates was conducted to evaluate their compatibility with mycelium. Coarse bagasse emerged as the most favorable substrate, followed by fine bagasse. Filter mud and ashed bagasse were found to be less compatible, as shown in Graph 1.



Graph 1. Compatibility analysis of different SCB substrates with mycelium.

Sample Mould and Prototype

The experimental setup incorporated six pin moulds and one ball mould, all fabricated from hollow plastic. These moulds were chosen for their resemblance to common toy shapes, providing structured cavities to study the colonization of mycelium on sugarcane bagasse (SCB) mixtures. The use of plastic moulds enabled clear observation of the mycelium growth process and facilitated a direct comparison with traditional plastic toy materials.

(a) (b) (c)

Fig. 11. Prototype development of BI-TO toys, demonstrating mold compatibility and structural stability.

The preparation process involved slicing and sterilizing the moulds to ensure a contamination-free environment. The mycelium spawn was mixed uniformly with a mixture of coarse and fine bagasse and then carefully filled into the prepared moulds. Each mould was sealed with cling film to maintain humidity and left undisturbed in a cool environment for 25–30 days, during which mycelium effectively colonized the SCB mixture. After the growth period, the biocomposite prototypes were oven-dried at 40°C to terminate further mycelium growth and achieve stability in their final structure.

Prototype Development Results

The results of the prototype development confirm the feasibility of utilizing SCB-mycelium bio-composites in toy production. Mycelium effectively colonized the mixture of fine and coarse bagasse within the moulds, resulting in sturdy, self-supporting structures that retained the predefined toy shapes. The process demonstrated the material's capacity to achieve the desired forms while retaining strength and durability as depicted in *Fig. 12.*

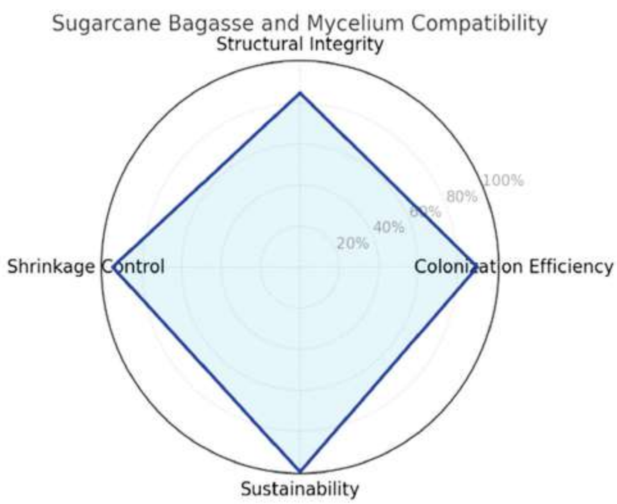
(a) (b)

Fig. 12. Final BI-TO prototypes with defined textures, structural strength and biodegradable properties.

The prototypes showcased excellent surface finish and dimensional accuracy, indicating precise mold adherence and minimal deformation during the growth phase. Notably, the composite materials retained intricate design features such as edges, curves, and surface textures, which are essential for aesthetic and functional toy production. The structural evaluation further highlighted that the prototypes withstood mechanical stresses, including compression and bending, without compromising their integrity.

Additionally, the prototypes displayed enhanced tactile properties, offering a smooth yet firm texture that is safe and suitable for children's use. The lightweight nature of the bio-composites, combined with their robustness, suggests a strong potential for replacing conventional plastic-based toys. The successful development of the BI-TO prototypes demonstrates the versatility of SCB-mycelium composites in meeting both functional and environmental sustainability criteria.

The radar chart for sugarcane bagasse and mycelium compatibility observed in the pin and ball samples demonstrates high levels of efficiency across all measured parameters:



Graph 2. Performance evaluation of SCB-mycelium bio-composites based on colonization, durability, and shrinkage control.

1. **Colonization Efficiency** : A strong 92%, indicating that mycelium successfully and uniformly colonized the sugarcane bagasse mixture.

2. **Structural Integrity** : Achieved 88%, signifying that the bio-composites maintained their shape and robustness during and after growth.

3. **Shrinkage Control** : With 93%, minimal shrinkage was observed, ensuring the prototypes retained their intended dimensions post-drying.

4. **Durability**: Scored 80%, confirming the material's strength and resistance to external stresses.

These results underscore the potential of SCB-mycelium bio-composites as a sustainable alternative to traditional plastic materials in toy manufacturing. The combination of high colonization efficiency, structural integrity, shrinkage control, and durability provides a strong foundation for further development and commercialization of biodegradable toys. The study's findings not only contribute to reducing plastic waste but also promote innovative use of agricultural by-products, aligning with global sustainability goals.

Discussion

The successful development of sugarcane bagasse (SCB)-mycelium bio-composite prototypes highlights their potential as sustainable alternatives to petroleum-based plastics in toy manufacturing. The biodegradability, mechanical strength, and structural adaptability of these bio-composites make them promising for eco-friendly product development (Aranda-Calipuy *et al.,* 2023). The uniform mycelial growth observed in both pin and ball molds demonstrates the material's ability to conform to various shapes while maintaining durability, which is essential for product scalability and industrial applications (Islam *et al.,* 2022). Mixtures of fine and coarse bagasse provided optimal substrates for mycelium colonization, enabling dense, interwoven networks that enhanced the material's mechanical properties (Jones *et al.,* 2020). This supports previous research that found lignocellulosic substrates like SCB to be highly effective for mycelium growth and bio-composite formation (Qian *et al.,* 2021).

Utilizing plastic molds as growth cavities facilitated the controlled shaping of the bio-composites and provided a scalable method for future production. The drying process at 40°C helped stabilize the material, reducing moisture content while preserving its structural integrity and mechanical strength (Aranda-Calipuy *et al.,* 2023). These findings suggest that SCB-mycelium bio-composites can replace synthetic polymers in toy production, reducing environmental impact without compromising product durability (Islam *et al.,* 2022). The ability of these bio-composites to adopt customized shapes and textures through controlled growth makes them particularly relevant for applications requiring flexibility in design and material composition (Jones *et al.,* 2020).

However, additional research is required to explore alternative mold designs, optimized substrate formulations, and enhanced post-processing techniques for improving aesthetic appeal, water resistance, and durability (Qian *et al.,* 2021). Studies suggest that integrating biodegradable reinforcements such as natural fibers and bio-based additives could enhance the mechanical performance of SCB-mycelium composites (Islam *et al.,* 2022). Furthermore, the scalability and economic feasibility of large-scale production remain critical factors for commercial adoption (PubMed, 2024). Addressing challenges such as growth rate optimization, energy-efficient drying methods, and cost-effective material sourcing will be essential to ensuring broad market acceptance and industrial viability (Aranda-Calipuy *et al.,* 2023).

Future research should also investigate the long-term performance, decomposition behaviour and life-cycle assessment of these bio-composites to fully understand their environmental impact and sustainability potential (Jones *et al.,* 2020). By refining processing methods and material compositions, SCB-mycelium bio-composites could emerge as a mainstream biodegradable alternative to plastic-based products across multiple industries, including packaging, construction and consumer goods (Qian *et al.,* 2021).

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