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Original Article

BioPotX: A Sustainable Waste-to-Wealth Innovation for Replacing Single-Use Plastic Nursery Containers

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ABSTRACT

The widespread use of single-use plastic nursery polybags has become a major environmental concern due to plastic pollution, microplastic accumulation, and disposal challenges. At the same time, agricultural residues such as rice straw (parali), fruit and vegetable waste, cow dung, and neem khali remain underutilized despite their potential as renewable resources. BioPotX is an innovative biodegradable nursery container developed using these organic waste materials to provide a sustainable alternative to conventional plastic polybags. The pot offers adequate mechanical strength during nursery operations, remains functional for approximately 2.5–6 months, and gradually biodegrades after transplantation without causing root disturbance. Its decomposition enriches soil organic matter, improves moisture retention, and enhances seedling establishment. By integrating waste valorization with sustainable nursery production, BioPotX promotes a circular bioeconomy approach that reduces plastic waste, minimizes stubble burning and landfill disposal, and supports environmentally sustainable horticulture.

Keywords: BioPotX, biodegradable nursery pot, rice straw, organic waste, waste-to-wealth.

1. INTRODUCTION

The horticulture and nursery sector plays a vital role in modern agriculture by producing high-quality seedlings for fruit crops, vegetables, ornamental plants, medicinal species, forestry plantations, and landscape development. Healthy nursery stock ensures better crop establishment, higher productivity, and improved post-transplant survival. Worldwide, nurseries predominantly use black polyethylene (PE) bags and plastic pots because of their low cost, durability, and ease of handling. However, the widespread use of these single-use plastic containers has become a major environmental concern due to their non-biodegradable nature and poor disposal practices.

Globally, billions of plastic nursery containers are consumed annually, with only a small proportion being recycled. Most are discarded into agricultural fields, municipal waste streams, or landfills, where they persist for decades. Environmental weathering causes these plastics to fragment into microplastics and nanoplastics, contaminating soil and water resources. Plastic residues adversely affect soil structure, microbial diversity, nutrient cycling, and root growth, posing significant challenges to sustainable agriculture. Consequently, the development of biodegradable alternatives to conventional plastic nursery containers has become an important research priority.

In addition to plastic pollution, crop residue management remains a major environmental challenge. India produces millions of tonnes of rice straw (parali) annually, much of which is burned in the field because of limited economic utilization and the short interval between successive crops. Stubble burning releases greenhouse gases and particulate matter, contributes to severe air pollution, destroys beneficial soil microorganisms, and results in the loss of valuable plant nutrients. Therefore, developing economically viable applications for rice straw is essential for reducing environmental degradation while promoting sustainable biomass utilization.

Rapid urbanization has also resulted in the generation of enormous quantities of biodegradable municipal waste. Fruit juice shops, vegetable markets, food processing units, and households produce large amounts of fruit pulp, peels, and vegetable residues that are often disposed of in landfills. Anaerobic decomposition of these wastes generates methane, a potent greenhouse gas, while valuable organic matter and nutrients remain underutilized. Recovering these biomass resources for agricultural applications offers an effective strategy for reducing waste disposal problems and promoting resource efficiency.

Another limitation of conventional nursery production is transplant shock. Seedlings must be removed from plastic containers before planting, frequently causing root damage that delays establishment, reduces water and nutrient uptake, and lowers survival rates. Biodegradable nursery containers that can be transplanted directly into the soil eliminate root disturbance, improve seedling establishment, and reduce labour requirements.

The circular bioeconomy provides an effective framework for addressing these interconnected challenges by converting renewable biomass residues into value-added products. Agricultural residues, livestock by-products, and biodegradable municipal wastes represent abundant renewable resources that can replace petroleum-based materials while simultaneously improving waste management, reducing greenhouse gas emissions, and enhancing resource-use efficiency.

Despite considerable research on biodegradable materials, there remains a need for nursery containers that combine adequate mechanical strength, controlled biodegradation, nutrient enrichment, and affordability. Most commercially available biodegradable pots rely on relatively expensive raw materials such as peat, coir, wood pulp, or biodegradable polymers, limiting their adoption, particularly in developing countries. Furthermore, limited efforts have focused on integrating multiple waste streams including rice straw, municipal organic waste, and livestock by-products into a single biodegradable nursery container.

To address these challenges, BioPotX has been developed as a biodegradable nursery container produced from rice straw (parali), processed fruit and vegetable waste, cow dung, and neem khali. Rice straw provides structural reinforcement, cow dung serves as a natural binder and microbial inoculant, fruit and vegetable waste contribute nutrients and organic matter, while neem khali offers antifungal and antimicrobial protection. The resulting biocomposite possesses sufficient mechanical strength during nursery production and gradually biodegrades after transplantation.

Unlike conventional plastic polybags, BioPotX can be transplanted directly into the field, eliminating transplant shock and allowing uninterrupted root growth. During decomposition, the container enriches the soil with organic matter, improves moisture retention, and supports microbial activity, thereby enhancing soil fertility while leaving no plastic residue. Simultaneously, the technology utilizes agricultural and municipal organic wastes that would otherwise contribute to stubble burning or landfill accumulation, thereby supporting environmental sustainability and resource recovery.

The present study aims to develop and optimize BioPotX using different formulations of rice straw, cow dung, fruit and vegetable waste powder, and neem khali to achieve suitable structural stability, controlled biodegradation, and desirable nursery shelf life. By integrating agricultural residue management with sustainable nursery production, BioPotX represents a practical waste-to-wealth innovation that supports circular bioeconomy principles and contributes to the achievement of Sustainable Development Goals (SDGs) 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land).

2. Problem Statement

The increasing demand for sustainable agricultural production has highlighted several environmental and operational challenges associated with conventional nursery practices. Plastic pollution, inefficient management of agricultural residues, improper disposal of biodegradable municipal waste, and poor seedling establishment due to transplant shock collectively threaten the sustainability of the horticulture sector. Although these issues are often addressed independently, they are closely interconnected and require an integrated solution. The BioPotX technology has been conceptualized to simultaneously address these challenges through a circular economy and waste-to-wealth approach.

2.1 Plastic Waste from Nurseries

The commercial nursery industry relies extensively on black polyethylene (PE) nursery bags because they are inexpensive, lightweight, and durable. However, these plastic containers are generally designed for single use and are discarded immediately after transplantation. Since polyethylene is non-biodegradable, the discarded bags remain in the environment for several decades, creating long-term ecological problems.

Improper disposal practices, including open dumping, burning, and burial, have become common in many developing countries where recycling infrastructure is inadequate. As these plastic bags undergo weathering due to sunlight, rainfall, and mechanical abrasion, they gradually fragment into microplastics and nanoplastics. These microscopic particles accumulate in agricultural soils, reduce soil quality, alter water infiltration and aeration, and adversely affect soil microorganisms responsible for nutrient cycling. Plastic residues can also obstruct irrigation channels and drainage systems, leading to waterlogging and increased maintenance costs.

Open burning of used plastic nursery bags further releases toxic pollutants such as carbon monoxide, dioxins, furans, and volatile organic compounds, posing significant risks to human health and the environment. With the expansion of horticulture, landscaping, and afforestation programmes, the consumption of plastic nursery containers continues to increase, making plastic waste management a major environmental concern. Therefore, replacing conventional plastic nursery bags with biodegradable alternatives has become an urgent priority for achieving environmentally sustainable nursery production.

2.2 Rice Straw (Parali) Burning

Rice is cultivated over millions of hectares in India, generating enormous quantities of rice straw as a by-product after harvest. Due to the short interval between rice harvesting and wheat sowing, combined with high labour and machinery costs for residue management, many farmers burn rice straw directly in the fields as the quickest and least expensive disposal method.

Stubble burning causes severe environmental degradation by releasing large quantities of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), along with particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide, and other hazardous pollutants. These emissions contribute to poor air quality, dense smog, reduced visibility, respiratory illnesses, cardiovascular diseases, and increased greenhouse gas concentrations.

The practice also causes substantial losses of valuable plant nutrients such as nitrogen, phosphorus, potassium, sulphur, and organic carbon that could otherwise be recycled back into agricultural soils. High temperatures generated during burning destroy beneficial soil microorganisms, reduce earthworm populations, impair soil structure, and decrease long-term soil fertility. Consequently, farmers become increasingly dependent on chemical fertilizers to maintain crop productivity.

Despite its abundance, rice straw is a lignocellulosic biomass rich in cellulose, hemicellulose, and lignin, making it a valuable renewable resource for developing biodegradable composite materials. However, limited commercial utilization has prevented its effective management. Developing value-added products such as biodegradable nursery pots offers an economically viable pathway for converting rice straw from an environmental liability into a valuable agricultural resource.

2.3 Municipal Organic Waste

Rapid urbanization and population growth have significantly increased the generation of biodegradable municipal solid waste. Every day, fruit juice shops, vegetable markets (mandis), food processing industries, hotels, restaurants, and households generate substantial quantities of fruit pulp, peels, spoiled vegetables, and kitchen waste.

Although these organic materials are rich in nutrients, cellulose, natural fibres, and biodegradable compounds, a considerable proportion remains unsegregated and is disposed of in open dumping sites or municipal landfills. Under anaerobic conditions, decomposition of organic waste produces methane, a greenhouse gas with approximately 28 times greater global warming potential than carbon dioxide over a 100-year period. Leachate generated from decomposing waste further contaminates soil and groundwater, creating additional environmental and public health concerns.

Municipal authorities spend considerable financial resources on collecting, transporting, and disposing of biodegradable waste, yet very little is converted into value-added products. The underutilization of fruit and vegetable waste represents a missed opportunity to recover nutrients and organic matter that could be beneficially used in agriculture. Incorporating processed fruit and vegetable waste into biodegradable nursery containers provides an innovative solution for waste valorization while simultaneously improving the nutrient content, moisture-holding capacity, and biodegradability of the final product.

2.4 Transplant Shock

Successful transplantation is one of the most critical stages in nursery management. Conventional nursery practices require seedlings to be removed manually from plastic bags before planting. During this process, root systems are frequently damaged due to tearing, compression, or disturbance of the soil-root interface.

Root injury reduces the plant's ability to absorb water and nutrients immediately after transplantation, leading to physiological stress commonly referred to as transplant shock. Affected seedlings often exhibit temporary wilting, reduced photosynthetic activity, slower growth, delayed establishment, and increased susceptibility to pests and diseases. In severe cases, transplant shock results in poor survival rates and significant economic losses for commercial nurseries and farmers.

The problem is particularly pronounced in horticultural crops, ornamental plants, medicinal species, and forestry seedlings where healthy root architecture is essential for rapid establishment and long-term growth. Moreover, the manual removal of plastic containers increases labour requirements and planting time, thereby raising production costs.

Biodegradable nursery containers eliminate the need to remove seedlings before transplantation. The entire pot can be planted directly into the soil, allowing roots to penetrate the decomposing container naturally. This minimizes root disturbance, improves moisture retention around the root zone, enhances nutrient availability during decomposition, and significantly increases transplant success. Consequently, biodegradable planting containers offer an effective solution for improving nursery efficiency while promoting sustainable crop establishment.

Need for an Integrated Waste to Wealth Solution

The challenges of plastic pollution, crop residue burning, municipal organic waste accumulation, and transplant shock are interconnected environmental and agricultural problems that require holistic rather than isolated solutions. Existing waste management practices often focus on disposal rather than resource recovery, while many biodegradable nursery products remain expensive due to the use of commercial raw materials such as peat, coir, or biodegradable polymers.

There is a pressing need for a cost-effective, environmentally friendly, and scalable technology capable of simultaneously utilizing agricultural residues, municipal organic waste, and livestock by-products to manufacture biodegradable nursery containers. Such a solution should possess adequate mechanical strength during nursery production, controlled biodegradation after transplantation, nutrient enrichment capability, and compatibility with existing nursery practices.

Concept Development, Material Composition and Functional Characteristics of BioPotX

BioPotX is an innovative biodegradable nursery container developed as a sustainable alternative to conventional single-use polyethylene nursery bags by utilizing locally available agricultural residues and biodegradable municipal organic waste. The technology is based on the principles of the circular economy and waste-to-wealth approach, wherein low-value biomass wastes are transformed into high-value horticultural products capable of reducing environmental pollution while simultaneously improving agricultural sustainability. Unlike conventional plastic nursery containers that persist in the environment for decades, BioPotX is designed to maintain adequate structural integrity during nursery operations and subsequently undergo controlled biodegradation after transplantation. As the container decomposes naturally in the soil, it enriches the rhizosphere with organic matter and nutrients, enhances microbial activity, improves soil moisture retention, and eliminates transplant shock by allowing uninterrupted root penetration through the degrading pot wall. Furthermore, the incorporation of natural bioactive materials imparts antifungal and antimicrobial properties, providing additional protection to young seedlings during the nursery stage.

The BioPotX composite is formulated using five major biodegradable raw materials, namely rice straw (parali), fruit waste powder, vegetable waste powder, cow dung, and neem khali. Each component contributes distinct structural, nutritional, and biological functions to the composite material. Rice straw, a lignocellulosic agricultural residue rich in cellulose and lignin, serves as the primary reinforcing fibre, enhancing the tensile strength and dimensional stability of the container while preventing structural collapse during irrigation and handling. Processed fruit and vegetable waste powders provide organic carbon, essential nutrients, natural polysaccharides, and biodegradable fibres that improve compost quality, moisture retention, and microbial decomposition during soil incorporation. Cow dung functions as a natural adhesive and structural matrix owing to its fibrous organic matter and beneficial microbial population, thereby improving cohesion among composite particles while promoting gradual biodegradation. Neem khali (neem cake) acts as a natural bioprotectant by providing antifungal, antimicrobial, and mild insect-repellent properties, while simultaneously supplying slow-release nutrients that support early plant growth.

To optimize the mechanical stability and degradation characteristics of the biodegradable container, three experimental formulations were developed using standardized cup-volume measurements. The first formulation (3:2:1) consisted of three parts cow dung, two parts rice straw, and one part fruit and vegetable waste powder, supplemented with neem khali. Owing to its relatively higher proportion of cow dung, this formulation exhibited superior binding capacity, greater compressive strength, enhanced durability, and an extended functional shelf life, making it suitable for raising larger fruit, ornamental, and forestry saplings. The second formulation (2:1:2) contained two parts cow dung, one part rice straw, and two parts fruit and vegetable waste powder with neem khali. This composition was characterized by increased nutrient availability, improved microbial activity, relatively faster biodegradation, and greater suitability for vegetable and short-duration horticultural seedlings. The third formulation (2:2:3) comprised two parts cow dung, two parts rice straw, and three parts fruit and vegetable waste powder along with neem khali. Due to its higher organic compost fraction, this formulation demonstrated superior water-holding capacity, rapid decomposition after transplantation, and greater soil organic matter enrichment, although with comparatively moderate mechanical strength. Comparative evaluation of these formulations facilitates optimization of the balance between structural durability during nursery growth and biodegradation following transplantation.

The manufacturing process of BioPotX begins with the systematic collection of agricultural residues, fruit waste, vegetable waste, cow dung, and neem khali from farms, juice vendors, vegetable markets, and livestock units. Fruit and vegetable wastes are thoroughly washed, segregated to remove contaminants, and dried under solar or mechanical conditions before being pulverized into a fine powder. Rice straw is chopped into short fibres to improve reinforcement and uniform mixing. The processed raw materials are subsequently blended according to the desired formulation ratio, followed by the addition of neem khali and sufficient water to obtain a homogeneous mouldable composite. The prepared mixture is compressed into nursery pot moulds using mechanical or manual compression techniques and dried under controlled air or solar conditions until the desired structural strength and moisture content are achieved. Finally, a biodegradable bio-protective coating is applied to both the inner and outer surfaces to improve water resistance, mechanical stability, and storage life without compromising biodegradability.

The developed BioPotX containers are expected to exhibit a functional nursery shelf life ranging from approximately 2.5 to 6 months depending on environmental conditions and formulation composition. Throughout the nursery period, the pots retain adequate structural integrity to withstand irrigation, handling, and transportation while remaining completely free from synthetic plastics. Following transplantation, gradual biodegradation allows unrestricted root penetration and eliminates transplant shock, thereby improving seedling establishment and survival. Simultaneously, decomposition releases valuable organic matter and nutrients into the surrounding soil, enhancing soil fertility, microbial biodiversity, and moisture-holding capacity. The incorporation of neem khali further provides natural antifungal protection, while the decomposed material ultimately becomes nutrient-rich compost without generating any environmentally persistent residues.

Beyond its functional performance as a nursery container, BioPotX offers substantial environmental, agricultural, and socioeconomic benefits. The technology contributes directly to reducing plastic pollution by replacing conventional polyethylene nursery bags with biodegradable alternatives, thereby preventing long-term accumulation of plastic waste and microplastics in agricultural soils. Simultaneously, productive utilization of rice straw offers a sustainable alternative to stubble burning, thereby reducing greenhouse gas emissions, particulate pollution, and nutrient losses associated with crop residue combustion. Valorization of fruit and vegetable wastes diverts significant quantities of biodegradable municipal waste away from landfills, minimizing methane emissions while recovering valuable organic resources. From an agronomic perspective, direct transplantation of BioPotX eliminates root disturbance, improves seedling survival, promotes rapid root establishment, enhances soil structure, conserves moisture, and gradually releases nutrients during decomposition, thereby reducing dependence on external soil amendments and lowering labour requirements during planting operations.

The versatility of BioPotX enables its application across a broad range of agricultural and horticultural systems, including commercial fruit nurseries, vegetable seedling production, ornamental horticulture, floriculture, forestry plantations, medicinal plant cultivation, urban gardening, terrace gardening, kitchen gardens, landscaping projects, afforestation programmes, and government-supported plantation initiatives. Owing to its biodegradable nature and nutrient-enriching properties, the technology is particularly suitable for sustainable and organic farming systems where minimizing synthetic inputs and environmental impacts is a major objective.

3. CONCLUSION

BioPotX represents an environmentally sustainable alternative to conventional plastic nursery containers by integrating agro-industrial residues and municipal organic waste into a biodegradable horticultural product. The developed formulations demonstrate the feasibility of converting rice straw, fruit and vegetable waste, cow dung, and neem khali into structurally stable nursery pots with a functional life of 2.5–6 months. Beyond replacing single-use plastics, BioPotX contributes to waste valorization, soil health improvement, reduced transplant shock, and enhanced resource-use efficiency. With further optimization through mechanical, biodegradation, and field performance studies, BioPotX has strong potential for commercialization as a scalable green technology supporting sustainable nursery production and circular economy development.