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Article

Carrot (*Daucus carota*) and Okra (*Abelmoschus esculentus*) wastes as sustainable feedstocks for Polyhydroxyalkanoate production by *Pseudomonas* species

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SUMMARY

The growing environmental concerns associated with non-biodegradable petroleum-based plastics have increased interest in sustainable alternatives such as polyhydroxyalkanoates (PHAs). PHAs are biodegradable and biocompatible biopolymers produced by various microorganisms as intracellular storage compounds. Despite their potential to replace conventional plastics, their large-scale production is constrained by high production costs. The use of agricultural waste as low-cost feedstocks offers a promising strategy for improving the economic viability of PHA production while promoting waste valorization. Carrot (*Daucus carota*) and okra (*Abelmoschus esculentus*) wastes are rich in fermentable carbohydrates and can serve as suitable substrates for microbial fermentation. Among PHA-producing microorganisms, *Pseudomonas* species are particularly important due to their metabolic versatility and ability to utilize a wide range of carbon sources. This review examines the production, properties, applications, benefits, and limitations of PHAs, with emphasis on the use of agricultural wastes and the potential of carrot and okra wastes as feedstocks for PHA production by *Pseudomonas* species. The challenges associated with commercial production and prospects for sustainable bioplastic development are also discussed.

Keywords: Polyhydroxyalkanoates (PHAs); *Pseudomonas* species; Carrot waste; Okra waste; Bioplastics

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INTRODUCTION

The widespread use of conventional petroleum-based plastics has contributed significantly to environmental pollution due to their persistence in terrestrial and aquatic ecosystems [1,2]. Growing concerns regarding plastic waste accumulation and its ecological impacts have increased interest in biodegradable and sustainable alternatives derived from renewable resources [3].

Polyhydroxyalkanoates (PHAs) are microbial polyesters that have emerged as promising substitutes for conventional plastics because of their biodegradability, biocompatibility, and physicochemical properties comparable to those of many synthetic polymers [4,5]. However, the high cost of PHA production remains a major challenge to their large-scale commercialization, particularly due to the expenses associated with carbon substrates and processing operations [9].

The use of agricultural and food-processing wastes as low-cost feedstocks has been widely explored as a strategy to improve the economic feasibility of PHA production [10,11]. Carrot (*Daucus carota*) and okra (*Abelmoschus esculentus*) wastes are rich in carbohydrates and other nutrients that can support microbial growth and biopolymer synthesis after appropriate pretreatment [12-15]. Among the various PHA-producing microorganisms, *Pseudomonas* species are of particular interest because of their metabolic versatility and ability to utilize diverse carbon sources for PHA accumulation [17].

This review explores the potential of carrot and okra waste as sustainable feedstocks for PHA production by Pseudomonas species and highlights current advances, challenges, and prospects.

Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) are biodegradable polyester synthesized intracellularly by numerous microorganisms as carbon and energy storage compounds under conditions of excess carbon and limited essential nutrients such as nitrogen or phosphorus [18,19]. Due to their biodegradability, biocompatibility, and physicochemical properties comparable to those of conventional plastics, PHAs have attracted considerable attention as sustainable alternatives to petroleum-based polymers [4,5].

PHAs consist of hydroxyalkanoate monomers and are classified into short-chain-length (scl-PHAs) and medium-chain-length (mcl-PHAs) polymers based on the number of carbon atoms in their monomer units [20]. Their properties vary depending on monomer composition, allowing the production of materials with different mechanical and thermal characteristics suitable for diverse applications [20].

Despite their environmental advantages, large-scale commercialization of PHAs remains constrained by high production costs associated with substrate utilization, fermentation processes, and downstream recovery operations [7,19]. Consequently, current research is focused on the use of inexpensive renewable feedstocks, including agricultural and food-processing wastes, to improve the economic feasibility of PHA production [10,11].

Classification and Properties of PHAs

Polyhydroxyalkanoates (PHAs) are classified according to the number of carbon atoms present in their monomer units. They are broadly grouped into short-chain-length PHAs (scl-PHAs), containing 3–5 carbon atoms, and medium-chain-length PHAs (mcl-PHAs), containing 6–14 carbon atoms [20,21]. Variations in monomer composition influence the physical, thermal, and mechanical properties of the resulting polymers, allowing the production of materials with diverse characteristics suitable for different applications [21].

PHAs possess several desirable properties, including biodegradability, biocompatibility, and thermoplasticity, which make them attractive alternatives to conventional petroleum-based plastics [4,5]. They can be completely degraded by microorganisms in natural environments and have been widely investigated for packaging, agricultural, and biomedical applications [22].

Biosynthesis of PHAs

PHAs are synthesized intracellularly by numerous microorganisms as storage compounds under conditions of excess carbon and limited essential nutrients such as nitrogen, phosphorus, or oxygen [18,19]. Under these conditions, microorganisms convert surplus carbon into PHA granules, which serve as reserves of carbon and energy for survival during unfavorable environmental conditions [19].

The accumulation of PHAs is influenced by microbial species, substrate type, and fermentation conditions. The accumulation of PHAs is influenced by microbial species, substrate type, and fermentation conditions. Volatile fatty acids obtained from food waste fermentation have recently emerged as promising carbon sources for microbial PHA production [16]. During fermentation, carbon substrates are metabolized and converted into hydroxyalkanoate monomers, which are subsequently polymerized and stored within the cell as PHA granules [19,23]. This ability to convert renewable carbon sources into biodegradable polymers has contributed to the growing interest in microbial PHA production.

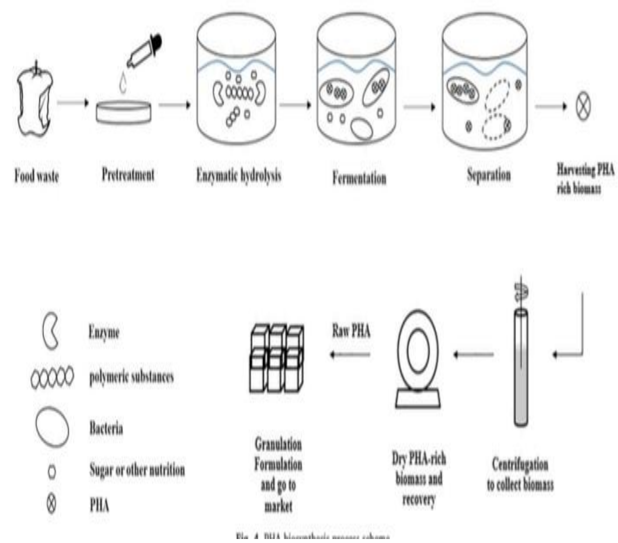

Figure 1: Schematic Representation of Microbial Polyhydroxyalkanoate (PHA) Biosynthesis **Source:** Tsang *et al.* (2019)

Microbial Production of PHAs

PHAs are synthesized by a wide range of microorganisms as intracellular carbon and energy reserves under conditions of excess carbon and limitation of essential nutrients such as nitrogen, phosphorus, or oxygen [25,26]. Several bacterial genera, including *Pseudomonas*, *Bacillus*, *Alcaligenes*, and *Cupriavidus*, have been reported as efficient PHA producers [27,28].

Among these microorganisms, *Pseudomonas* species are particularly important because of their metabolic versatility and ability to utilize diverse carbon sources, including agricultural and food-processing wastes, for PHA accumulation [17,29]. This capability makes them attractive candidates for sustainable and cost-effective bioplastic production from renewable feedstocks.

Pseudomonas Species as PHA Producers

Pseudomonas species are among the most extensively studied microorganisms for polyhydroxyalkanoate (PHA) production because of their metabolic versatility and ability to utilize a wide range of carbon substrates, including agricultural and food-processing wastes [17,19]. They can synthesize mainly medium-chain-length PHAs (mcl-PHAs), which possess desirable mechanical and thermal properties suitable for industrial and biomedical applications [2,22].

The efficiency of PHA accumulation by *Pseudomonas* species is influenced by factors such as the type of carbon source, nutrient limitation, fermentation conditions, and strain characteristics [17,19]. Optimization of culture conditions and advances in metabolic engineering have been reported to improve polymer yield and productivity [17]. However, the high cost of fermentation substrates and downstream processing remains a major limitation to commercial-scale production. Consequently, current research is focuses on the use of inexpensive renewable feedstocks and improved fermentation strategies to enhance the economic feasibility of PHA production by *Pseudomonas* species [10,11,17].

Applications of Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) have attracted considerable attention because of their biodegradability, biocompatibility, and versatile physicochemical properties, making them suitable for biomedical, industrial, agricultural, and packaging applications [30–40].

In the biomedical field, PHAs are widely used in tissue engineering, wound dressings, surgical sutures, bone and cartilage regeneration, and controlled drug delivery systems due to their excellent biocompatibility and non-toxic degradation products [4,30,31]. Their ability to degrade gradually in the body also makes them suitable for implantable medical devices.

Industrially, PHAs are increasingly used as sustainable alternatives to petroleum-based plastics in food packaging, disposable consumer products, coatings, fibers, and electronic components. Their thermoplastic properties, good gas barrier performance, and biodegradability make them suitable for packaging applications while reducing dependence on fossil-based plastics [5,22,32,33,37,38].

In agriculture, PHAs are applied in biodegradable mulch films, seed coatings, controlled-release fertilizers, and pesticide delivery systems. They degrade naturally in soil, minimizing plastic waste and reducing the need for removal after use [31,34].

Overall, the wide range of PHA applications demonstrates their potential to replace conventional plastics in several sectors while promoting environmental sustainability and supporting the transition toward a circular bioeconomy [3,35-40].

CONCLUSION

Polyhydroxyalkanoates (PHAs) are environmentally friendly biopolymers with great potential to replace conventional plastics. The use of carrot and okra wastes as renewable feedstocks, together with the metabolic versatility of *Pseudomonas* species, offers a sustainable and cost-effective approach to PHA production. Although challenges related to production cost and large-scale commercialization remain, continued research and process optimization are expected to enhance the feasibility and wider adoption of PHA-based bioplastics.

Declarations

Author's Contributions

A.M.M. conceived the study, conducted the literature review, and prepared the first draft of the manuscript. A.M.S., E.E.O., and S.L.A. critically reviewed the manuscript and provided intellectual input. All authors contributed to the development of the final manuscript and approved its submission

Disclosure of Conflict of Interest

None

Ethics Approval and Informed Consent

This study did not use human or animal subjects. Therefore, ethical consideration was not applicable

Disclosure of Funding

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