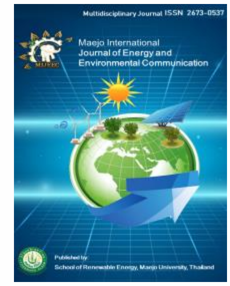
Maejo International Journal of Energy and Environmental Communication 5-3 (2023) 52-58

Maejo International Journal of Energy and Environmental Communication

Journal homepage: https://ph02.tci-thaijo.org/index.php/MIJEEC



ARTICLE

Techno-economic feasibility analysis on sustainability polyhydroxy-alcanoates production process transitions from high-strength organic wastewater

Mingyan Shen[1,2,3], Vannasinh Souvannasouk[4], Sasithorn Saipa[1], Chen-Yeon Chu[2,5,6]*, Nuttiya Tantranont[7], Chayanon Sawatdeenarunat[1,], Chen-Hua Hsueh[6], Hsuan-Chen Wu[3]**

[1]Asian Development College for Community Economy and Technology, Chiang Mai Rajabhat University, Chiang Mai, Thailand
[2]Master’s Program of Green Energy Science and Technology, Feng Chia University, Taichung, 407102, Taiwan
[3]Department of Biochemical Science and Technology, National Taiwan University, Taipei 10617, Taiwan.
[4]Faculty of Economics and Management, Champasak University, Champasak, Lao PDR
[5]Institute of Green Products, Feng Chia University, Taichung, 407102, Taiwan
[6]General Education Center, Feng Chia University, Taichung, 407102, Taiwan
[7]Faculty of Education, Chiang Mai Rajabhat University, Chiang Mai, Thailand

ARTICLEINFO

Article history:
Received 03 November 2023
Received in revised form
01 December 2023
Accepted 05 December 2023

Keywords:
PHA production
Mixed microbial cultures
Techno-Economical analysis
High organic wastewater
Sensitivity analysis

ABSTRACT

Polyhydroxyalcanoates (PHAs) are promising biodegradable plastics that can replace conventional petroleum-based plastics and mitigate oceanic pollution. High organic wastewater has been examined as a potential substrate for lowering the manufacturing cost of PHAs. In this study, the three main indicators, including net present value (NPV), internal rate of return (IRR), and payback period (PBP), were used to calculate the economic feasibility of PHA production. For a project lifetime of 20 years, the cost of the PHA manufacturing process reached $994,143. The annual process operation cost was $159,711. The payback period was 6.79 years, and the internal return rate was 16%. However, if costs increased by 20%, the benefits would decrease by 25%. Since the price of PHAs is higher than that of conventional plastic, various government supports are expected to stimulate the market of PHAs potentially. This study successfully determines the techno-economic analysis of PHA production to form high-strength wastewater with MMC as the microbial source.

1. Introduction

The use of plastics has increased dramatically since the 1950s due to numerous advantages, such as their versatility and resistance (Schmaltz et al., 2020). In 2015, the weight of the annual plastic production was nearly equal to the combined weight of the human population (Martín-Lara et al., 2021). Due to the surge in production and extensive use of disposable plastic products, plastic pollution has become an urgent environmental issue (Lu et al., 2018). Many

* Corresponding author.
E-mail address: cychu@fcu.edu.tw (Chu C.Y.) chayanon@cmru.ac.th (Sawatdeenarunat C.)

nations are implementing efforts to combat plastic pollution at regional, national, and global scales, for example, choosing other materials as a substitute. Bioplastics are eco-friendly materials that can replace petroleum-based plastics since they are biodegradable and made from renewable resources (Lamberti et al., 2020).

Biodegradable bioplastics can significantly reduce carbon emissions associated with the exploitation of resources (Di Bartolo et al., 2021). Over the past few decades, there have been numerous launches of bioplastics products, including polylactic acid (Guo et al. 2021), polyhydroxyalkanoates (PHAs) (Shen et al., 2023), polybutylene succinate (Nanni et al., 2021), and thermoplastic starch (Dorigato et al., 2020). Additionally, there are bio-polyethylene terephthalate (bioPET) and bio-polyethylene (bioPET), which resemble non-renewable substances (Rahman et al., 2021). However, although bioplastics have been in commercial use for nearly a century, the sales volume has not grown significantly. Based on the 2019 study conducted by the European Bioplastics Association, the worldwide output of bioplastics in 2018 amounted to 2.11 million tons, which represented 0.6 percent of the total plastic production (Niaounakis, 2019). It is projected to increase to 289 million tons by the year 2025. Bioplastics are expected to have significant growth in market share in the near future. This is primarily driven by the global shift away from petroleum-based plastics towards biodegradable alternatives, which aims to address environmental issues (Serafim et al., 2008).

PHAs have gained attention recently due to their numerous advantages, such as easy synthesis, UV resistance, and durability (Gholami et al., 2016; Mannina et al., 2019). These properties make them suitable substitutes for polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP).

The PHA production process is divided into acidification, PHA production, and downstream processing. Firstly, carbon sources are converted to VFA in a fermentation process. Secondly, PHA is produced in the mixed microbial cultures (MMC) cells following the acidification process by utilizing VFA. The downstream process (DSP) is the final stage for extracting PHA from the microbial cells. Following these three techniques, PHA can be synthesized as bioplastic materials (Fernández et al., 2015). The method of producing PHA using various engineered microbial communities has been proposed as a potential technique to reduce production costs and environmental harm. However, the majority of the research was done on the production of PHAs using pure cultures or pure substrates such as acetate and glucose (Serafim et al., 2008), and, as a result, PHA has become a prohibitively expensive material driven by the high production cost. Due to their natural origin, biodegradability, and functionality, PHAs have attracted considerable interest as a viable alternative to traditional plastics. However, the production cost of PHAs is high, projected to be 20–80% higher than those associated with petrochemical-based plastics (Fernández et al., 2015).

The price of PHAs polymer is between 2.2 and 5.0 Euros per kilogram, while that of traditional oil-based plastic is always less than 1 Euro per kilogram. In other words, the price of PHA is approximately three times higher, which is destined to hinder the utilization of this bioplastic (Gholami et al., 2016; Mannina et al., 2019). Triggered by the need to expand bioplastic usage, this research aims to perform the techno-economic analysis of the PHA production to form high-strength waste (i.e., molasses) by using MMC as the microbial source.

2. Materials and methods

2.1 Scope of PHA production process

The boundaries for this study's techno-economic analysis of the PHA production process include acidification, PHA accumulation, and downstream processing (DSP), as presented in Figure 1. The lifetime of the equipment of the PHA production system is assumed to be 20 years, as recommended by Fernández-Dacosta et al. (2015) and Shahzad et al. (2017). Acidification is the first step of PHA production (Salehizadeh & Van, 2004). The COD concentration of the molasses used in this study was 556 g/L, which would be anaerobically converted to the VFA throughout this bioprocess. The produced VFAs included acetic acid of 4087 mg/L, propionic acid of 2430 mg/L, and butyric acid of 8151 mg/L. These VFAs subsequently served as a substrate for the process of PHA accumulation. During the accumulation process in a sequencing batch reactor (SBR), MMC could aerobically produce PHA from the acidification process and accumulate in their cells. Thus, PHA-rich biomass was obtained as a main product of the PHA accumulation. However, the PHA cannot be used while located inside the biomass. The DSP is the final process for extracting the VFA produced from the microbial cells as the final product.

DSP starts with separating biomass via physical methods. After that, there are two options for PHA extraction: (1) chemical digestion or mechanical disruption is used to dissolve the non-cellular PHA material, and (2) solvent extraction is used to solubilize the PHA. Following the extraction stage, precipitation, filtration, sedimentation, and other options for higher-value products, such as liquid-liquid extraction or air classification, are applied. PHA must be purified in the final phase by redissolving it in water or ethanol. Numerous DSPs are available, including alkali-surfactant (Li et al., 2015), surfactant-hypochlorite, and dichloromethane solvent (Serafim et al., 2008). The DSP model in this study uses the extraction method with a dichloromethane (DCM)--based solvent. The advantage of this method is the high efficiency achieved in extracting intracellular PHA. DCM can produce PHA with a purity of 99.9% by weight at a boiling point of 40 degrees Celsius. Because of the low boiling point, it is simpler to recycle the solvent, and the entire process consumes low energy. The extracted PHA could be as high as 82.2% by biomass weight (Fernández-Dacosta et al., 2015).

2.2 Techno-Economic evaluation of PHA production process

The PHA production process is typically divided into three stages: acidification, PHA production, and downstream processing. The acidification process is the initial step in the production of PHA. Firstly, significant carbon sources are biologically converted to VFA

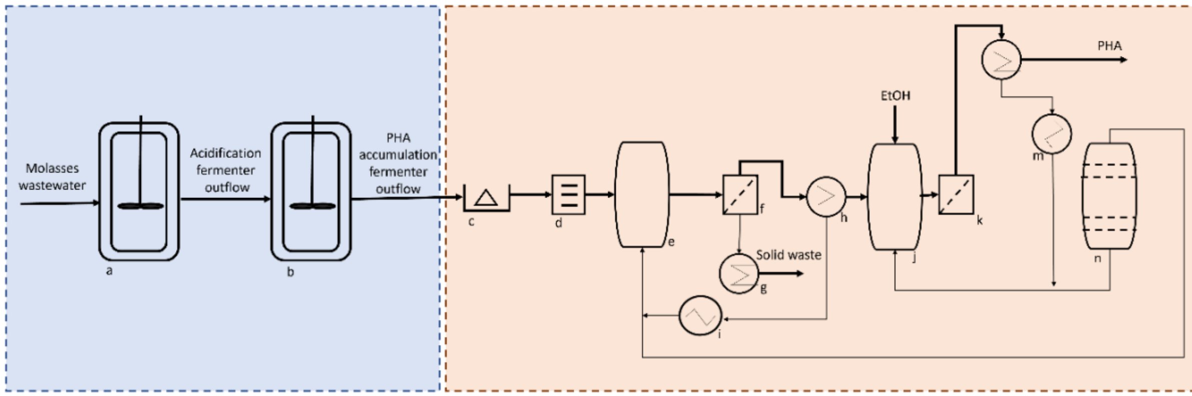


Figure 1 The process of PHA production. (a. acidification fermenter, b. PHA accumulation fermenter, c. centrifuge, d. air dryer, e. DCM reactor, f. filter, g. solid phase dryer, h. DCM evaporator, i. DCM condenser, j. ethanol precipitation reactor, k. filter, l. dryer, m. condenser, n. vacuum distillation.)

in a fermentation process. Secondly, the mixed microbial cultures (MMC) produce and accumulate PHA in their cells following the acidification process by utilizing VFA generated from the first step; consequently, the PHA-rich biomass is obtained. However, the accumulated PHA cannot be used inside the cell. The downstream process (DSP) is the final stage for extracting the produced PHA from the microbial cells. Following these three techniques, PHA can be synthesized as bioplastic materials. The literature compared the capacity for producing PHA using various substrates and cultures and evaluated the most economically advantageous from a technological standpoint.

In this study, the four main indicators, including net present value (NPV), benefit-cost ratio (BCR), internal rate of return (IRR), and payback period (PBP), were used to calculate the economic feasibility of PHA production. The project was estimated for a period of 20 years with a discount rate of 8% (Gunjal & Amankwah, 1999) and a loan interest rate of 7.9% (Shi et al., 2021). A sensitivity analysis was then used to evaluate a projected return on investment based on cost increase and profit decline assumptions of the 6.25 CMD PHA production system.

2.3 Statistical analysis

The studies were performed thrice, presenting the findings as the average value plus or minus the standard deviation. The statistical analysis was conducted using the SPSS program, and significance was evaluated.

3. Results and discussion

3.1 PHA production yield analysis

Table 1 shows a comparative analysis of the prior research on PHA production involving the utilization of various substrates or different microbial cultures. Several researchers studied municipal wastewater, protein-rich saline waste, and food industrial wastewater as substrates to produce PHA facilitated by MMC (Morgan-Sagastume et al., 2015; Roibás-Rozas et al., 2021; Lai et al. 2022). The PHA production yields were around 40% to 42%. Mohanrasu et al. (2024) and Zhang et al. (2013) used a commercial medium to produce PHA by pure culture, while the PHA yields were 54% and 39%, respectively. However, the PHA production yield of 53.3% was obtained by using the molasses wastewater as the substrate with MMC as the inoculum in this study. The production yield of PHA of 54% was slightly 0.7% (Table 1) higher than this study since the pure substrate of glucose was used for PHA production by pure culture (Mohanrasu et al., 2024). However, a cost-effective PHA production process could be expected if the PHA production system can reach a high-yield production performance from high-strength organic wastewater by MMC. Hence, the economic assessment was done as follows in Table 1.

3.2 Basic information of the PHA production process

The PHA manufacturing process consists of three stages, as mentioned in section 2.1. The size of PHA's production system in this study is assumed to be 6.25 cubic meters per day (CMD) of molasses. The concentration of molasses waste was 556 g COD/L, but it was diluted to the final concentration of 25 g COD/L. The molasses substrate costs $20,531 annually (Arshad et al., 2019). The sizes of acidification and PHA accumulation systems were estimated to be 500 m2 and 300 m2, respectively. This study assumed the project's lifetime was 20 years (Fernández-Dacosta et al., 2015; Shahzad et al., 2017). Since the acidification and PHA accumulation systems are similar to the two-stage biogas production system, the installation cost for both systems were approximately $555,387 (Li et al., 2015). The model solvent used in this experiment was assumed to be dichloromethane. Because DCM is a solvent similar to chloroform, it could extract 82% PHA from the biomass (Fernández-Dacosta et al., 2015). Accordingly, the cost of DSP was higher than the cost of fermentation. DCM could contribute to approximately 79% of the total cost of the PHA-producing process. In this study, the price of DSP was estimated to be $438,756. The total capital cost of the PHA manufacturing process was $994,143.

As presented in Table 1, the assumptions for techno-economic analysis are the capital cost of PHA production, which included acidification, PHA accumulation, and DSP, with an amount of $994,143 (Fernández-Dacosta et al., 2015; Arshad et al., 2019). The maintenance cost was 3% of the capital costs, the labour cost was 10% of the capital costs, and utilities constituted 1% of the capital costs. The overall operation cost was $159,711, including maintenance, labour, utilities, and materials. The revenue came from the produced PHAs (Fernández-Dacosta et al., 2015). In this study, the yield of PHAs was assumed to be 53.58% PHA/VSS. The DSP in this study could extract up to 82.2% from the biomass as aforementioned. Thus, 227 kgs of PHA were estimated to be produced daily, or 82,890 kgs of PHA could be produced annually. The selling price of PHA was $4/kg. Thus, the total revenue of this process was $330,753 per year.

Table 1 PHAs production yield and rate in different substrate and microbial cultures

Substrate	Culture	Reactor type	PHAs production yield (%)	Reference
Municipal wastewater	Mixed culture	Sequencing batch reactor	40.0 PHAs/VSS	Morgan-Sagastume et al. (2015)
Protein-rich saline waste	Mixed culture	Sequencing batch reactor	42.0 PHAs/VSS	Roibás-Rozas et al. (2021)
Food industry wastewater	Mixed culture	Sequencing batch reactor	40.0 PHB/VSS	Lai et al. (2022)
Glucose	Bacillus megaterium	Batch	54.0 PHAs/CDW	Mohanrasu et al. (2024)
Luria-Bertani (LB) broth	Pseudomonas putida	Batch	39.0 PHAs/CDW	Mohanrasu et al. (2024)
Molasses wastewater	Mixed culture	Sequencing batch reactor	53.3 PHA/VSS	This study

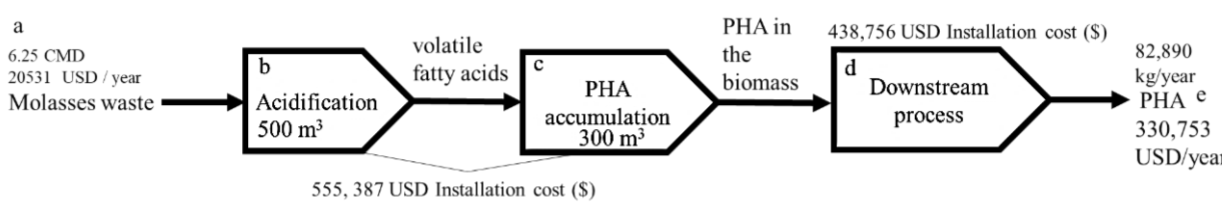


Figure 2 The diagram of PHA production with its size and cost: (a) substrate (Arshad et al., 2019), (b) acidification fermenter, (c) PHA accumulation fermenter, (b+c) (Li et al., 2015), (d) DSPs (Fernández-Dacosta et al., 2015), (e) PHA product price (Gholami et al., 2016; Mannina et al., 2019) production process: A, B (Arshad et al., 2019; Fernández-Dacosta et al., 2015), C,D,E (Fernández-Dacosta et al., 2015), F (Arshad et al., 2019), G (Gholami et al., 2016)

Table 2 The total cost of PHA production processes

Items	PHA production process (USD)
Capital cost	
Capital investment (A)	994,143
Operation costs (C+D+E+F=B)	
Maintenance (C) (3% of capital costs)	29,824
Labour (D) (10% of capital costs)	99,414
Utilities (E) (1% of capital costs)	9,941
Material (F)	20,531
Total (A+B)	159,711
Revenue	
PHA ($4/kg) (G)	330,753

Table 3 Economic analysis of PHA production

Project	NPB* (USD)	NPC* (USD)	NPV* (USD)	BCR (NPB/NPC)	PBP (year)	IRR (%)
PHAs production	$2,948,300	$2,340,690	$607,733	1.26	6.79	16.31

*Assumption of the project period for 20 years; Assumption of the discount rate of 8% (Gunjal & Amankwah, 1999); Assumption of the loan interest rate of 7.9% (Zhang et al., 2013)

3.3 Techno-economic evaluation

As given in Table 2, the study's results showed that the NPV for the PHAs duction system was positive and the BCR was greater than one; thus, the proposed project was considered financially feasible (Gunjal & Amankwah, 1999). Second, the average interest rate on loans offered by Taiwan Bank was 7.9% from July 1961 to March 2017 (Zhang et al., 2013), and the IRR results indicated that the annual rate of return of 16.3% was for 20 years. The IRR of PHAs' production system in this study was 8.4% higher than the interest rate on loans in Taiwan. This proves that it is worth investing in the project. The PBP in this study was 6.21 years, compared with the 3.25–4.5-year PBP from the study (Shahzad et al., 2017). Although many revenue-generating fuels exist, including biodiesel, biogas (heat and electricity), and PHA, this study focuses on PHA production and is the only revenue-generating system. As a result, this system is absolutely worth investing.

The price of PHA to be calculated in this study is $4/kg. This is the average price of PHA (Mannina et al., 2019). As per the result of sensitive analysis, when the revenue of PHA decreases by 20%, it is still profitable. That is to say, the price of PHA in this system can be $3.2/kg. The production cost of fossil-based plastics is less than $1 per kilogram (Gholami et al., 2016). Therefore, upgrading PHA's production technology will be a challenge in the future. According to the findings of the sensitive analysis, the PHA project remains a worthy investment even if the total revenue is reduced by 20%. Consequently, the price of PHA could be as low as $3.2/kg, compared with the current average price of $4/kg (Mannina et al., 2019). As the production cost of fossil plastics is less than $1/kg (Gholami et al., 2016), improving the production technology has become a critical issue for future developments of PHA.

3.4 Sensitivity analysis

Figure 3 shows the PHA project's sensitivity analysis as costs increase. The total cost of the PHA project from the base case scenario is $4,028,656, with an NPV of $607,609. Assuming that the total cost of the PHA project is increased by 5% due to the current inflation rate, the total cost would increase to $4,231,088, and the NPV would be decreased to $425,600. The PHA project would still have a positive NPV even if the total cost of the PHA project increases up to 15%. Nonetheless, the project would not be worth an investment if it increased to 20% of the total cost due to the negative results of the NPV.

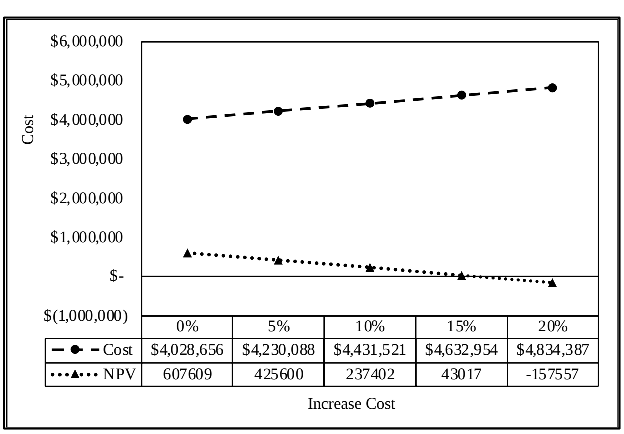


Figure 3 Increasing PHA project cost

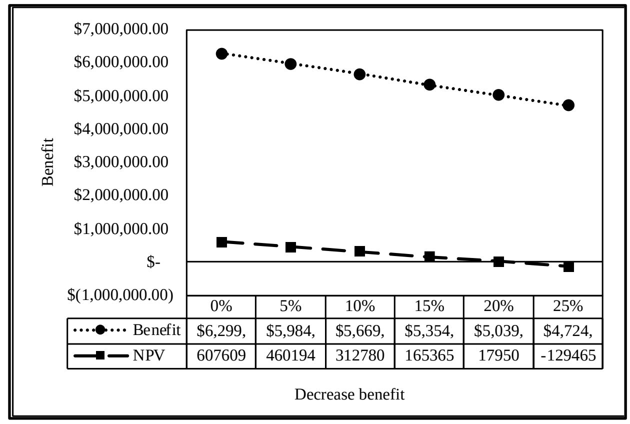


Figure 4 Decrease in PHA project benefits

As presented in Figure 4, the total revenue of this PHA project was $6,299,628, and the NPV over the long run was $607,609. This PHA project was supposed to decrease the total revenue by 5% in each sensitive analysis because of the inflation rate under the current economic situation. The total revenue of the PHA project would decrease from $6,299,628 to $5,984,647, and the NPV for the project would decrease from $607,609 to $460,194. Nonetheless, if the total profit of the project decreased by 25%, the NPV would be negative, and this PHA project would not be accepted for investment.

3.5 Sustainable development

There is rising concern among global communities and governments regarding the severe negative impact of using nonbiodegradable and conventional plastics on the environment (Bhuyar et al., 2020). Uncontrolled disposal of plastics in the environment could cause sewer blockage and environmental exposure. The problem is exacerbated by the lack of municipal infrastructure that could be utilized to collect the plastic frequently used in packaging our daily necessities. As a result, substantial pollution has accumulated over time and overrun the streets and other public spaces. Because plastic waste dissipates natural fuels (energy) and other natural resources, it has posed major environmental and economic problems (Varsha & Savitha, 2011). As public awareness of the harmful effects of plastics on the humans and the environment has grown, several countries have taken steps to address the issue at the regional, national, and global levels. Thus, utilizing PHAs could mitigate the environmental impact apart from achieving economic competitiveness.

Plastic bags have a significant environmental impact because they take hundreds of years to decompose. Approximately 34 million tons of plastic waste are generated yearly, with approximately 93% disposed of through landfills and oceans (Pathak et al., 2014). In 2015, it was reported that production of plastics and plastic-derived materials exceeded 300 million tons, equivalent to trillions of dollars in global economic value (Mekonnen et al., 2013). Consequently, the world urgently requires environmentally friendly plastic substitutes. In this regard, PHAs appear to be a possible solution to common plastics because they are environmentally friendly due to their high biodegradability and biocompatibility.

Bio-based plastics such as the PHA family of polymers are known for their environmental-friendly characteristics. PHAs are biodegradable and sourced from the bacterial consumption of glucose or fatty acids. They not only contain zero percent petrochemical monomers; also, they are biological polymers created in an aqueous phase at temperatures of <40 °C (Chen & Patel, 2012). Furthermore, carbon waste sources derived from agriculture and the sewage treatment system have been used to reduce the cost of PHA production. The waste carbon is thus coupled with the added value as it purifies the environment and realizes sustainable goals.

4. Conclusion

The results indicated that the 6.25 CMD PHA production system was financially feasible under the base run scenario. The NPV of the PHA production system was larger than 0, and the BCR of the PHA production system was larger than 1. The PBP was 6.79 years old, and the IRR of 16% was larger than the global interest rate and the interest rate on loans from Taiwan Bank. This was absolutely a worthwhile investment. The sensitivity analysis mentioned that the NPV would be less than zero when the cost in this study was increased by 20%, or the benefit was reduced by 25%. This means that this project has a great ability to withstand economic changes. The use of high organic wastewater with MMC is certainly the way of the future, and adding pyruvate can improve PHA output production while also changing the PHV ratio in PHA. Systems that employ wastewater to make PHAs are commercially viable for locations of medium to largescale, and PHA is the future trend.

Acknowledgement

The authors gratefully acknowledge the financial support from the National Science and Technology Council, Taiwan (grant numbers: NSTC 111-2221-E-035 -040 -MY3; 112-2927-I-035-501; 112-2923-E-035-001-MY3; 112-2218-E-035-002).

Ethical statement

We would like to declare that the work was original research that has not been published yet, also not under consideration for publication in another journal.

Competing interests

The authors have no competing interests regarding the subject of this research article.

Author Contributions

Conceptualization, Chayanon Sawatdeenaruna, Chen-Yeon Chu and Hsuan-Chen Wu; methodology, Chen-Yeon Chu, Chayanon Sawatdeenaruna, Vannasinh Souvannasouk and Ming-Yan Shen; software, Vannasinh Souvannasouk and Ming-Yan Shen; validation, Chen-Yeon Chu, Chayanon Sawatdeenarunat, Nuttiya Tantranont and Hsuan-Chen Wu; formal analysis, Vannasinh Souvannasouk, Nuttiya Tantranont, Sasithorn Saipa and Ming-Yan Shen; investigation, Ming-Yan Shen, Vannasinh Souvannasouk; resources, Chen-Yeon Chu, Chen-Hua Hsueh and Chayanon Sawatdeenarunat; writing—original draft preparation, Ming-Yan Shen, Sasithorn Saipa, Chen-Hua Hsueh; writing—review and editing, Chen-Yeon Chu, Chen-Hua Hsueh, Chayanon Sawatdeenaruna and Nuttiya Tantranont; visualization; supervision, Chen-Yeon Chu, Chayanon Sawatdeenarunat and Hsuan-Chen Wu; funding acquisition, Chen-Yeon Chu and Chayanon Sawatdeenarunat; All authors have read and agreed to the published version of the manuscript.

Data availability

Data sharing does not apply to this article.

References

Bhuyar, P., Rahim, M. H. A., Sundararaju, S., Ramaraj, R., Maniam, G. P., & Govindan, N. (2020). Synthesis of silver nanoparticles using marine macroalgae Padina sp. and its antibacterial activity towards pathogenic bacteria. Beni-Suef University Journal of Basic and Applied Sciences, 9, 1-15.

Chen, G. Q., & Patel, M. K. (2012). Plastics derived from biological sources: present and future: a technical and environmental review. Chemical reviews, 112(4), 2082-2099.

Di Bartolo, A., Infurna, G., & Dintcheva, N. T. (2021). A review of bioplastics and their adoption in the circular economy. Polymers, 13(8), 1229.

Dorigato, A., Perin, D., & Pegoretti, A. (2020). Effect of the temperature and of the drawing conditions on the fracture behaviour of thermoplastic starch films for packaging applications. Journal of Polymers and the Environment, 28, 3244-3255.

Fernández-Dacosta, C., Posada, J. A., Kleerebezem, R., Cuellar, M. C., & Ramirez, A. (2015). Microbial community-based polyhydroxyalkanoates (PHAs) production from wastewater: Techno-economic analysis and ex-ante environmental assessment. Bioresource technology, 185, 368-377.

Arshad, M., Abbas, M., & Iqbal, M. (2019). Ethanol production from molasses: Environmental and socioeconomic prospects in Pakistan: Feasibility and economic analysis. Environmental Technology & Innovation, 14, 100317.

Gholami, A., Mohkam, M., Rasoul-Amini, S., & Ghasemi, Y. (2016). Industrial production of polyhydroxyalkanoates by bacteria: opportunities and challenges. Minerva Biotechnol, 28(1), 59-74.

Gunjal, K., Owusu-Manu, M., Ramaswamy, H. S., & Amankwah, F. (1999). Minimal processing of fish and pork in Quebec: a financial feasibility.

Guo, X., Yao, Y., Zhao, H., Chi, C., Zeng, F., Qian, F., Liu, Z., Huo, L., & Lv, Y. (2021). Environmental impacts of functional fillers in polylactide (PLA)-based bottles using life cycle assessment methodology. Science of The Total Environment, 788, 147852

Lai, C. W., Bhuyar, P., Shen, M. Y., & Chu, C. Y. (2022). A Two-stage strategy for polyhydroxybutyrate (PHB) production by continuous Biohydrogen fermenter and sequencing batch reactor from food industry wastewater. Sustainable Energy Technologies and Assessments, 53, 102445.

Lamberti, F. M., Román-Ramírez, L. A., & Wood, J. (2020). Recycling of bioplastics: routes and benefits. Journal of Polymers and the Environment, 28(10), 2551-2571.

Li, J., Kong, C., Duan, Q., Luo, T., Mei, Z., & Lei, Y. (2015). Mass flow and energy balance plus economic analysis of a full-scale biogas plant in the rice–wine–pig system. Bioresource technology, 193, 62-67.

Lu, L., Guest, J. S., Peters, C. A., Zhu, X., Rau, G. H., & Ren, Z. J. (2018). Wastewater treatment for carbon capture and utilization. Nature Sustainability, 1(12), 750-758.

Mannina, G., Presti, D., Montiel-Jarillo, G., & Suárez-Ojeda, M. E. (2019). Bioplastic recovery from wastewater: A new protocol for polyhydroxyalkanoates (PHA) extraction from mixed microbial cultures. Bioresource Technology, 282, 361-369.

Martín-Lara, M. A., Godoy, V., Quesada, L., Lozano, E. J., & Calero, M. (2021). Environmental status of marine plastic pollution in Spain. Marine pollution bulletin, 170, 112677.

Mekonnen, T., Mussone, P., Khalil, H., & Bressler, D. (2013). Progress in bio-based plastics and plasticizing modifications. Journal of Materials Chemistry A, 1(43), 13379-13398.

Mohanrasu, K., Rao, R. G. R., Dinesh, G. H., Zhang, K., Prakash, G. S., Song, D. P., Muniyasamy, S., Pugazhendhi, A., Jeyakanthan, J., & Arun, A. (2020). Optimization of media components and culture conditions for polyhydroxyalkanoates production by Bacillus megaterium. Fuel, 271, 117522.

Morgan-Sagastume, F., Hjort, M., Cirne, D., Gérardin, F., Lacroix, S., Gaval, G., Karabegovic, L., Alexandersson, T., Johansson, P., Karlsson, A., & Werker, A. (2015). Integrated production of polyhydroxyalkanoates (PHAs) with municipal wastewater and sludge treatment at pilot scale. Bioresource technology, 181, 78-89.

Nanni, A., Cancelli, U., Montevecchi, G., Masino, F., Messori, M., & Antonelli, A. (2021). Functionalization and use of grape stalks as poly (butylene succinate)(PBS) reinforcing fillers. Waste Management, 126, 538-548.

Niaounakis, M. (2019). Recycling of biopolymers–the patent perspective. European Polymer Journal, 114, 464-475.

Pathak, S., Sneha, C. L. R., & Mathew, B. B. (2014). Bioplastics: its timeline based scenario & challenges. Journal of Polymer and Biopolymer Physics Chemistry, 2(4), 84-90.

Pedras, B., Salema-Oom, M., Sá-Nogueira, I., Simões, P., Paiva, A., & Barreiros, S. (2017). Valorization of white wine grape pomace through application of subcritical water: Analysis of extraction, hydrolysis, and biological activity of the extracts obtained. The Journal of Supercritical Fluids, 128, 138-144.

Rahman, M. H., & Bhoi, P. R. (2021). An overview of non-biodegradable bioplastics. Journal of cleaner production, 294, 126218.

Roibás-Rozas, A., Del Rio, A. V., Hospido, A., & Mosquera-Corral, A. (2021). Strategies for the valorisation of a protein-rich saline waste stream into polyhydroxyalkanoates (PHA). Bioresource Technology, 334, 124964.

Salehizadeh, H., & Van Loosdrecht, M. C. M. (2004). Production of polyhydroxyalkanoates by mixed culture: recent trends and biotechnological importance. Biotechnology advances, 22(3), 261-279.

Schmaltz, E., Melvin, E. C., Diana, Z., Gunady, E. F., Rittschof, D., Somarelli, J. A., Virdin, J., & Dunphy-Daly, M. M. (2020). Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. Environment international, 144, 106067.

Serafim, L. S., Lemos, P. C., Albuquerque, M. G., & Reis, M. A. (2008). Strategies for PHA production by mixed cultures and renewable waste materials. Applied microbiology and biotechnology, 81, 615-628.

Shahzad, K., Narodoslawsky, M., Sagir, M., Ali, N., Ali, S., Rashid, M. I., Ismail, I.M.I., & Koller, M. (2017). Techno-economic feasibility of waste biorefinery: Using slaughtering waste streams as starting material for biopolyester production. Waste management, 67, 73-85.

Shen, M. Y., Chu, C. Y., Sawatdeenarunat, C., & Bhuyar, P. (2023). Production, downstream processing, and characterization of polyhydroxyalkanoates (PHAs) boosted by pyruvate supplement using mixed microbial culture (MMC) and organic wastewater. Biomass Conversion and Biorefinery, 13(17), 15861-15869.

Shi, Z., Zhang, L., Yuan, H., Li, X., Chang, Y., & Zuo, X. (2021). Oyster shells improve anaerobic dark fermentation performances of food waste: Hydrogen production, acidification performances, and microbial community characteristics. Bioresource Technology, 335, 125268.

Varsha, Y. M., & Savitha, R. (2011). Overview on polyhydroxyalkanoates: a promising biopol. J. Microb. Biochem. Technol, 3(05), 99-105.

Zhang, Y., Liu, H., Liu, Y., Huo, K., Wang, S., Liu, R., & Yang, C. (2021). A promoter engineering-based strategy enhances polyhydroxyalkanoate production in Pseudomonas putida KT2440. International Journal of Biological Macromolecules, 191, 608-617.

Zhang, Wen, Eric S. McLamore, N. T. Garland, JV Chavez Leon, and M. Katherine Banks. "A simple method for quantifying biomass cell and polymer distribution in biofilms." Journal of microbiological methods 94, no. 3 (2013): 367-374.