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PUMAKKAL AS A LOCAL INDIGENOUS BACTERIAL CONSORTIUM FOR PINEAPPLE WASTEWATER BIOREMEDIATION, ORGANIC WASTE VALORIZATION, AND CIRCULAR AGRICULTURE

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A B S T R A C T

Pineapple-processing wastewater is generally acidic and contains high organic loads that may degrade environmental quality when discharged without adequate treatment. This article analyzes Pumakkal as a local microbial innovation based on an indigenous bacterial consortium derived from pineapple wastewater for bioremediation, organic waste valorization, and circular agriculture. This study employed an integrative review with a research-based innovation case synthesis by synthesizing laboratory, pilot-scale, limited-scale, ex situ, and applied studies on Pumakkal. The synthesis focused on indigenous bacterial isolation and characterization, consortium formulation, hydrolytic capacity, bioremediation performance based on pH, biochemical oxygen demand, chemical oxygen demand, total suspended solids, fish viability as a supporting bioindicator, and applications of Pumakkal in organic waste conversion. The findings show that Pumakkal was developed from 15 indigenous bacterial isolates with hydrolytic capacities toward organic substrates, particularly starch, protein, and lipids. The complete consortium improved pineapple wastewater quality by increasing pH toward near-neutral conditions and reducing biochemical oxygen demand, chemical oxygen demand, and total suspended solids under reported testing conditions. Fish bioindicator observations further suggest that bioremediated effluent has better relative biological compatibility than untreated wastewater. Pumakkal has also been applied to several organic wastes to produce nutrient-containing fertilizer materials, indicating its potential role in waste-to-resource transformation. The strongest evidence supports Pumakkal's relevance to SDG 6 through wastewater quality improvement and SDG 12 through organic waste utilization, while its links to SDG 2 and SDG 4 are better read as downstream implications requiring further agronomic and educational validation. Broader implementation requires molecular identification, biosafety assessment, process standardization, field-scale validation, and long-term agronomic testing..

INTRODUCTION

Pineapple-processing industries generate large amounts of wastewater and solid residues, particularly in tropical production centers such as Lampung Province, Indonesia. Although this agroindustry contributes to regional economic activity, its wastewater can create serious environmental problems when discharged without adequate treatment. Pineapple wastewater is commonly characterized by low pH, high organic matter content, and elevated biochemical oxygen demand, chemical oxygen demand, and total suspended solids. Previous studies reported that pineapple-processing wastewater may have highly acidic conditions, with pH values of approximately 2.0–4.5, and substantial organic loads that can reduce dissolved oxygen, disturb aquatic organisms, generate unpleasant odors, and degrade water and soil quality (Sutanto, 2012a, 2012b). These characteristics point to the need for treatment strategies that are effective in reducing pollutant loads and compatible with local environmental and economic conditions.

Conventional waste management approaches that rely mainly on disposal, dilution, or end-of-pipe treatment are insufficient for addressing agroindustrial waste in a sustainable manner. In the context of circular bioeconomy, organic waste should be viewed as more than a pollutant. It is also a biological resource that can be recovered, transformed, and reintegrated into productive systems. Microorganisms play a central role in this transformation because they can degrade complex organic compounds, reduce pollutant concentrations, and support nutrient recovery from waste streams (Atasoy et al., 2023). Pineapple wastewater management should accordingly be directed toward biological treatment systems that combine pollutant reduction with waste valorization.

Microorganism-based bioremediation offers a promising approach for treating organic-rich wastewater. Compared with physical and chemical treatments, bioremediation utilizes microbial metabolism to transform organic pollutants through processes that are generally more environmentally friendly and potentially more affordable for local applications. Recent studies in environmental microbiology emphasize that microbial communities contribute to pollutant degradation, nutrient recycling, ecosystem restoration, and circular bioeconomy development (Bîrgovan et al., 2025; D'hondt et al., 2021; Philp, 2021). Yet bioremediation effectiveness depends strongly on the compatibility between microbial agents and wastewater characteristics. In acidic wastewater with high organic load, microorganisms that are not adapted to such conditions may show limited survival, unstable activity, or reduced degradation performance.

The use of indigenous or autochthonous bacteria is therefore relevant for pineapple wastewater bioremediation. Indigenous bacteria are naturally associated with their source environment and may have better adaptability to local physicochemical conditions, including low pH and high concentrations of organic substrates. Previous studies suggest that indigenous microorganisms can support contaminant degradation and wastewater treatment because they are already adapted to the environmental pressures present in the waste matrix (N. Das et al., 2025). In pineapple wastewater, indigenous bacteria matter for more than pollutant reduction. The wastewater itself can serve as a reservoir of functional microorganisms for local biotechnological innovation.

The performance of indigenous bacteria can be strengthened through microbial consortium formulation. Agroindustrial wastewater commonly contains diverse organic substrates, including carbohydrates, proteins, lipids, and other complex compounds that may not be efficiently degraded by a single bacterial isolate. A bacterial consortium can provide complementary metabolic functions, allowing different isolates to act on different substrate fractions and improve the stability of organic matter degradation. Studies on microbial consortia show that mixed bacterial communities may perform better than single isolates in treating complex pollutants because of functional complementarity and metabolic cooperation (Atasoy et al., 2023; S. Das et al., 2023). Some bacteria can also produce extracellular enzymes and biosurfactants that improve substrate availability and accelerate degradation processes (Dias & Nitschke, 2023; Gupta et al., 2025).

Pumakkal is a local microbial innovation developed from indigenous bacteria isolated from pineapple wastewater. Previous Pumakkal studies reported 15 indigenous bacterial isolates with hydrolytic capacities toward organic substrates, particularly protein, starch, and lipids. These isolates have been formulated as bacterial consortia and evaluated for their ability to improve pineapple wastewater quality by increasing pH and reducing biochemical oxygen demand, chemical oxygen demand, and total suspended solids (Sutanto, 2012a, 2012b). Beyond wastewater treatment, Pumakkal has also been applied in the processing of several organic wastes into nutrient-containing fertilizer materials, suggesting that Pumakkal functions as both a bioremediation agent and a microbial platform for waste-to-resource transformation within circular agriculture (Błaszczyk et al., 2024; El-Ramady et al., 2022).

Despite increasing attention to organic waste bioremediation, indigenous microorganisms, and agroindustrial waste valorization, several gaps remain. Many bioremediation studies still emphasize pollutant reduction, whereas the connection between wastewater treatment and resource recovery is less explicitly developed (Chatterjee et al., 2024; Venkatesham et al., 2025; Zabermawi et al., 2022). In addition, although indigenous bacterial consortia have been studied in several wastewater contexts, consortia derived directly from pineapple wastewater remain relatively limited (Bhtnagar & Kalra, 2022; Rai et al., 2024; Sutanto, 2012a; Sutanto et al., 2020). The integration of bioremediation, organic waste valorization, and circular agriculture within a single local microbial innovation framework is also still underreported, despite growing interest in circular bioeconomy and agro-waste utilization (El-Ramady et al., 2022; Santos et al., 2024; Sharma et al., 2022). Furthermore, research-based microbial innovations are not always positioned as contextual biology learning resources, although local environmental issues can support microbiology, environmental biotechnology, and sustainability education (Anggarawati et al., 2024; Sidik et al., 2020; Yulita et al., 2024). In this article, however, the educational dimension is treated only as a downstream implication rather than as direct evidence of learning effectiveness.

Based on these gaps, this article analyzes Pumakkal as a local indigenous bacterial consortium for pineapple wastewater bioremediation, organic waste valorization, and circular agriculture. Specifically, this article examines the development of Pumakkal as a research-based microbial innovation, its reported performance in improving pineapple wastewater quality based on pH, biochemical oxygen demand, chemical oxygen demand, and total suspended solids, its application in converting organic waste into fertilizer materials, and its relevance to selected Sustainable Development Goals. The main contribution of this article is the synthesis of Pumakkal as a local microbial innovation framework that connects indigenous bacterial potential, agroindustrial wastewater treatment, waste-to-resource transformation, and contextual biology learning. The Pumakkal innovation pathway is presented in Figure 1.

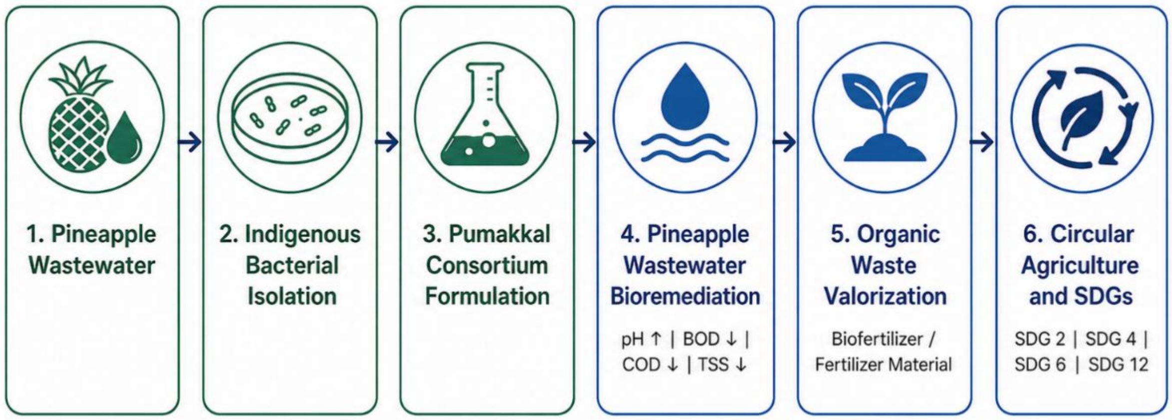

Figure 1. Pumakkal innovation pathway for bioremediation and circular agriculture.

METHODOLOGY

This study employed an integrative review with a research-based innovation case synthesis. This approach was selected because Pumakkal was not developed through a single experiment, but through a series of related studies involving pineapple wastewater characterization, indigenous bacterial isolation, isolate characterization, consortium formulation, laboratory-scale bioremediation, limited-scale validation, ex situ testing, fish bioindicator observation, and applications in organic waste processing. The purpose of this approach was to synthesize available evidence into a coherent local microbial innovation framework for pineapple wastewater bioremediation, organic waste valorization, circular agriculture, and contextual biology learning.

The main object of analysis was Pumakkal, an indigenous bacterial consortium derived from pineapple wastewater. The analyzed aspects included the characteristics of pineapple wastewater, the number and characteristics of indigenous bacterial isolates, hydrolytic capacities of the isolates, bacterial consortium formulation, bioremediation performance, fish bioindicator response, application of Pumakkal in organic waste conversion, and relevance to selected Sustainable Development Goals. The analysis therefore did not focus on a single experimental parameter, but on the connection between microbial potential, pollutant reduction, waste-to-resource transformation, and sustainability-oriented application.

The sources included in this synthesis were selected based on their direct relevance to Pumakkal development and application. The inclusion criteria were studies that reported at least one of the following aspects: pineapple wastewater characteristics, indigenous bacterial isolation, bacterial hydrolytic capacity, Pumakkal consortium formulation, wastewater bioremediation performance, fish bioindicator observation, organic waste conversion, fertilizer-material characteristics, or biology learning implications related to Pumakkal. Sources that only mentioned Pumakkal without presenting relevant empirical data or application evidence were not used as primary evidence. Both quantitative and qualitative data were included, provided that the source contained traceable information related to Pumakkal development or application.

Table 1. Analytical domains, evidence sources, indicators, and synthesis direction.

Analytical domain	Evidence source	Main indicators	Synthesis direction
Microbial innovation	Studies on indigenous bacterial isolation and Pumakkal formulation	Number of isolates, tentative bacterial identity, hydrolytic capacity	Explaining Pumakkal as a local indigenous bacterial consortium
Pineapple wastewater bioremediation	Laboratory, pilot-scale, limited-scale, and ex situ studies	pH, biochemical oxygen demand, chemical oxygen demand, total suspended solids	Evaluating reported wastewater quality improvement after Pumakkal treatment
Bioindicator response	Fish viability observation in treated and untreated wastewater	Fish survival/viability during observation	Supporting interpretation of relative effluent safety
Organic waste valorization	Studies applying Pumakkal to shrimp-pond waste, noodle-production waste, fish-market waste, pineapple residues, and other organic wastes	Nitrogen, phosphorus, potassium, organic carbon, carbon-to-nitrogen ratio, pH, micronutrients	Assessing the potential of Pumakkal in waste-to-resource transformation
Sustainability and learning relevance	Synthesis of bioremediation, valorization, SDG mapping, and learning-resource studies	SDG 6, SDG 12, SDG 2, SDG 4, contextual biology learning potential	Mapping direct contributions and downstream implications

The data were grouped into five analytical domains. The first domain was microbial innovation, which included the origin of Pumakkal, the number of bacterial isolates, tentative bacterial identity, and hydrolytic capacities toward starch, protein, and lipids. The second domain was pineapple wastewater bioremediation, which included changes in pH, biochemical oxygen demand, chemical oxygen demand, and total suspended solids. The third domain was organic waste valorization, which included applications of Pumakkal in converting different organic wastes into nutrient-containing fertilizer materials. The fourth domain was sustainability and education relevance, which included mapping to selected Sustainable Development Goals and potential use as a contextual biology learning resource.

The main bioremediation indicators were pH, biochemical oxygen demand, chemical oxygen demand, and total suspended solids. These indicators were used because they represent acidity, organic pollutant load, and suspended particle content in wastewater. Changes in pH were used to evaluate the capacity of Pumakkal treatment to shift acidic pineapple wastewater toward a more neutral condition. Biochemical oxygen demand and chemical oxygen demand were used to indicate changes in biodegradable and chemically oxidizable organic loads, while total suspended solids were used to describe changes in suspended matter. Fish viability was used as a supporting biological indicator to compare the relative response of aquatic organisms in bioremediated effluent and untreated pineapple wastewater.

For the organic waste valorization domain, the analysis focused on the reported capacity of Pumakkal to support the conversion of organic waste into fertilizer materials. The evaluated parameters included nitrogen, phosphorus, potassium, organic carbon, carbon-to-nitrogen ratio, pH, and selected micronutrients, depending on the original study. These data were not treated as equivalent across all waste types because each substrate has different composition, moisture content, nutrient content, and contaminant risk. Therefore, the valorization evidence was interpreted according to the type of waste, formulation, fermentation condition, and context of the original study.

Data analysis was conducted descriptively and integratively. Quantitative bioremediation data were synthesized by comparing reported wastewater quality before and after Pumakkal treatment, particularly for pH, biochemical oxygen demand, chemical oxygen demand, and total suspended solids. Fish viability data were interpreted as supporting bioindicator evidence rather than as a complete ecological safety assessment. Organic waste valorization data were analyzed by comparing reported nutrient characteristics and their relevance to waste-to-resource transformation. The results were then mapped to selected Sustainable Development Goals based on the strength of evidence: SDG 6 and SDG 12 were treated as the most directly supported domains, while SDG 2 and SDG 4 were interpreted as downstream implications requiring further agronomic and educational validation.

To maintain interpretive accuracy, this article limits its claims to the evidence available from the Pumakkal research series. Bioremediation claims are limited to reported improvements in pineapple wastewater quality under specific testing conditions. Organic waste valorization claims are limited to the potential conversion of waste into fertilizer materials, not to universal agronomic effectiveness across crops and environments. Educational claims are limited to the potential use of

Pumakkal as a contextual biology learning resource, not to direct evidence of improved learning outcomes. Broader implementation of Pumakkal therefore requires further molecular identification of bacterial isolates, biosafety assessment, process standardization, field-scale validation, and long-term evaluation of agronomic effectiveness.

RESULTS AND DISCUSSION

Pumakkal as an Indigenous Bacterial Consortium from Pineapple Wastewater

The synthesis shows that Pumakkal was developed from 15 indigenous bacterial isolates derived from pineapple wastewater. These isolates showed morphological and physiological diversity and hydrolytic capacity toward several organic substrates. In the Pumakkal research series, several isolates were reported to belong to the genera *Bacillus*, *Acinetobacter*, *Klebsiella*, *Pseudomonas*, and *Actinobacillus* (Sutanto, 2012a; Sutanto et al., 2020), but these taxonomic identities should be read cautiously, based on the available identification methods in the original studies. Further molecular confirmation is still required before the consortium can be standardized for broader environmental or agricultural applications.

The presence of indigenous bacteria in pineapple wastewater shows that this waste stream is a source of pollution as well as a reservoir of locally adapted microorganisms. Indigenous or autochthonous microorganisms are relevant for bioremediation because they may be more compatible with the physicochemical conditions of their original environment, including acidic pH and high organic load (Bhtnagar & Kalra, 2022; Rai et al., 2024). In the case of pineapple wastewater, this adaptation is important because microbial agents used for treatment must be able to function under acidic and organic-rich conditions.

Functionally, Pumakkal isolates have been reported to hydrolyze starch, protein, and lipids. These hydrolytic capacities indicate enzymatic potential for breaking down complex organic substrates into simpler compounds (Sutanto et al., 2020). Amylolytic isolates may contribute to carbohydrate degradation, proteolytic isolates to protein breakdown, and lipolytic isolates to lipid degradation. These complementary functions provide the biological basis for formulating Pumakkal as a bacterial consortium rather than relying on a single isolate.

The use of a 15-isolate consortium may offer functional advantages because different isolates can contribute different degradation capacities. In complex organic waste systems, bacterial consortia can be more effective than single isolates when members of the consortium perform complementary metabolic roles. This interpretation is consistent with studies showing that bacterial consortia can improve bioremediation efficiency in organic wastewater treatment compared with single strains (Thamaraiselvi et al., 2025). The potential effectiveness of Pumakkal should thus be understood as a product of both indigenous adaptation and functional complementarity among isolates.

Pumakkal Performance in Pineapple Wastewater Bioremediation

Pumakkal bioremediation performance was evaluated based on pH, biochemical oxygen demand, chemical oxygen demand, and total suspended solids. These parameters are relevant because they represent acidity, organic pollutant load, and suspended matter in wastewater. The available studies showed that Pumakkal treatment improved pineapple wastewater quality by increasing pH and reducing biochemical oxygen demand, chemical oxygen demand, and total suspended solids (Sutanto et al., 2020). The summarized evidence is presented in Table 2.

Table 2. Summary of Pumakkal bioremediation performance in pineapple wastewater.

Testing stage	**Condition/treatment**	**Main result**
Laboratory/in vitro test	Complete 15-isolate consortium	pH reached 5.92; BOD 49.23 mg/L; COD 30.00 mg/L; TSS 27.67 mg/L
Pilot-scale test	5% starter with 6-day incubation	BOD reduction efficiency 49.22%; COD reduction 52.02%; TSS reduction 28.14%
Limited-scale validation	Pumakkal treatment on pineapple wastewater	pH increased from 3.05 to 7.15; BOD decreased from 596 to 39.575 mg/L; COD decreased from 1595.5 to 94.99 mg/L; TSS decreased from 261 to 53 mg/L
Ex situ test	Pumakkal treatment under conditions closer to environmental application	pH increased from 2.95 to 7.60; BOD decreased from 665.75 to 28.33 mg/L; COD decreased from 1061.70 to 77.60 mg/L; TSS decreased from 138.95 to 22.00 mg/L

The data in Table 2 show that Pumakkal treatment was associated with a shift in pineapple wastewater from strongly acidic conditions toward near-neutral pH. This change is important because low-pH wastewater can disturb aquatic organisms and affect environmental quality when released without treatment. The ex situ data showed that pH increased from 2.95 to 7.60, indicating a substantial improvement under the reported testing conditions, though it should be read as evidence of treatment performance in the tested system, not as proof that the same outcome will occur under all industrial wastewater conditions.

The decreases in biochemical oxygen demand and chemical oxygen demand indicate a reduction in organic pollutant load. Biochemical oxygen demand reflects the oxygen required for microbial decomposition of biodegradable organic matter, while chemical oxygen demand reflects the oxygen required for chemical oxidation of organic compounds. The ex situ data showed that biochemical oxygen demand decreased from 665.75 to 28.33 mg/L and chemical oxygen demand decreased from 1061.70 to 77.60 mg/L. These reductions suggest that organic matter in the wastewater was substantially degraded during Pumakkal treatment. The reduction in total suspended solids, from 138.95 to 22.00 mg/L in the ex situ test, also indicates a decrease in suspended particles that may contribute to turbidity and ecological disturbance. Reductions in biochemical oxygen demand, chemical oxygen demand, and total suspended solids are commonly used as indicators of improved wastewater treatment performance (Chatterjee et al., 2024; Zabermawi et al., 2022).

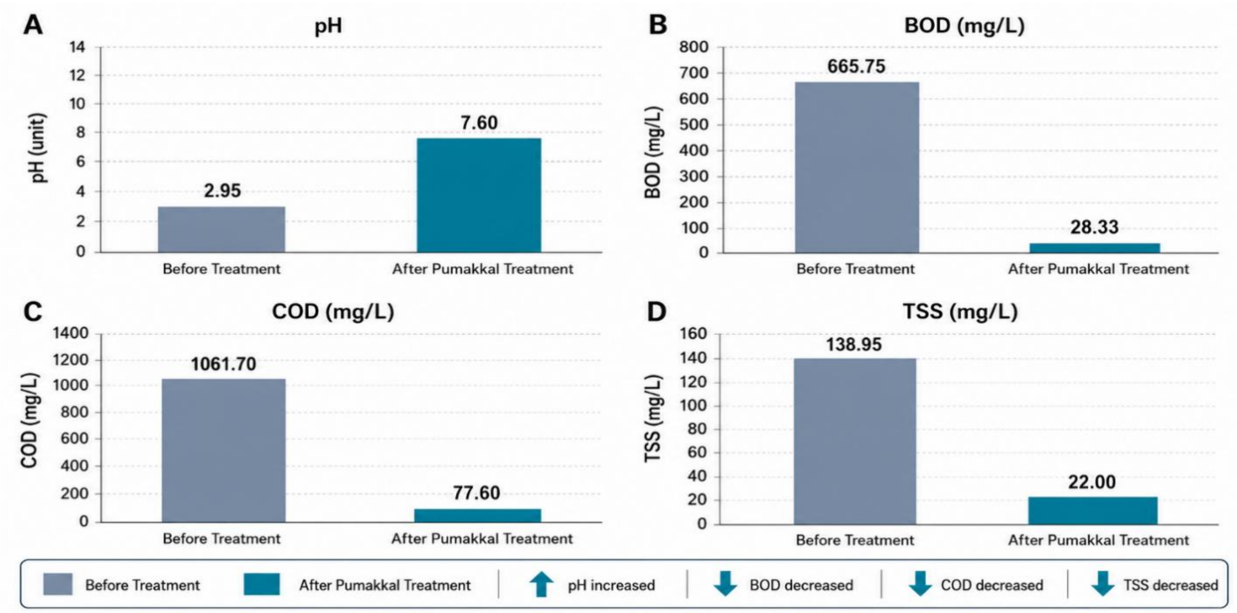

Figure 2. Ex situ Pumakkal bioremediation performance based on pH, biochemical oxygen demand, chemical oxygen demand, and total suspended solids before and after treatment.

The strongest reported performance was observed in treatments using the complete 15-isolate consortium. This finding supports the assumption that functional diversity within the consortium may contribute to the degradation of different organic fractions in pineapple wastewater. Isolates with amylolytic, proteolytic, and lipolytic capacities may act on carbohydrates, proteins, and lipids, respectively. Thus, Pumakkal is better interpreted as a multi-functional bacterial consortium rather than a single-pathway bioremediation agent. This interpretation aligns with microbiome innovation studies emphasizing that microbial functional diversity can support more sustainable environmental management systems (D'hondt et al., 2021).

Nevertheless, the bioremediation findings should remain proportional. The available data indicate improved wastewater quality under specific laboratory, pilot-scale, limited-scale, and ex situ testing conditions. They do not yet prove that Pumakkal will produce identical performance across different pineapple-processing industries, wastewater compositions, treatment volumes, environmental temperatures, incubation times, starter doses, or aeration regimes. Further work is required to evaluate process stability, operational scalability, biosafety, and compliance with applicable wastewater discharge standards.

Effluent Validation Using Fish Bioindicators

Alongside physicochemical parameters, fish viability was used as supporting biological evidence to compare Pumakkal-bioremediated effluent with untreated pineapple wastewater. The available observation showed that fish placed in medium A, namely Pumakkal-bioremediated effluent, survived longer than fish placed in medium B, namely untreated pineapple wastewater (Sutanto et al., 2020). This pattern suggests that physicochemical improvement after Pumakkal treatment was associated with lower biological stress on simple aquatic organisms under the tested conditions.

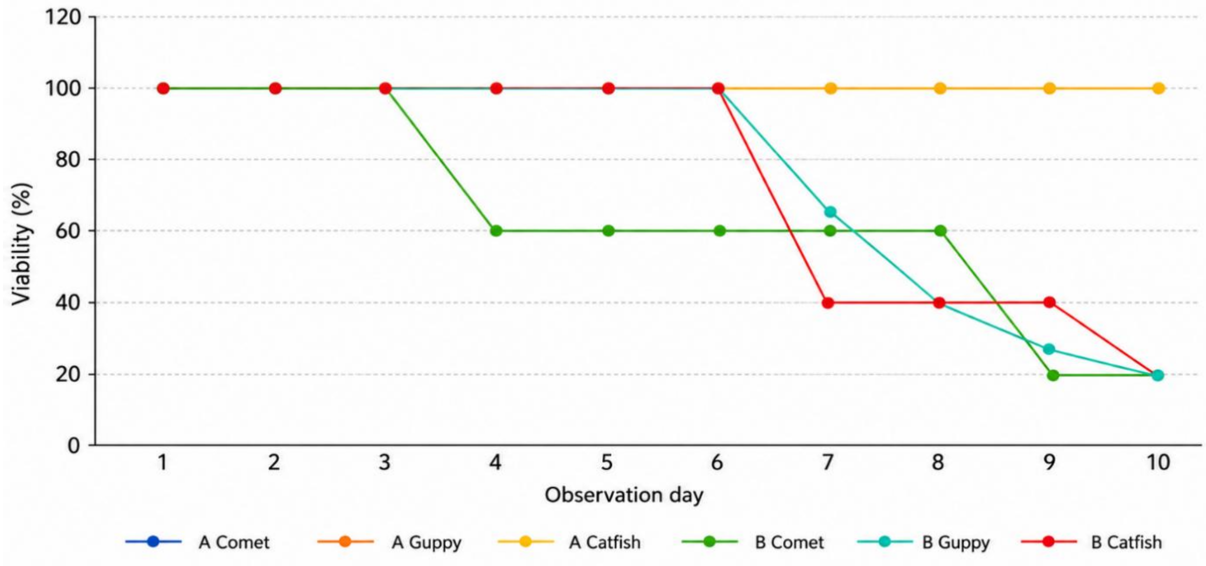

Figure 3. Fish viability during 10 days of observation in medium A (Pumakkal-bioremediated effluent) and medium B (untreated pineapple wastewater), using comet fish, guppy, and catfish as bioindicators.

The use of fish as bioindicators provides an additional perspective because physicochemical parameters alone do not always capture biological responses to wastewater. An effluent with reduced biochemical oxygen demand or chemical oxygen demand may still contain compounds that affect living organisms, which is why fish viability can function as supportive evidence in evaluating relative effluent quality (Zabermawi et al., 2022). In this article, the fish observation is useful for strengthening the interpretation that Pumakkal treatment improved the biological compatibility of pineapple wastewater compared with untreated wastewater.

Even so, this evidence should not be overinterpreted. Fish viability under limited observation conditions does not constitute a complete ecological safety assessment. It does not replace chronic toxicity testing, pathogen-risk analysis, microbial biosafety evaluation, chemical residue analysis, or long-term monitoring of receiving water bodies, so the fish bioindicator data should be presented as supporting evidence of relative effluent improvement, not as definitive proof that the treated effluent is environmentally safe under all application contexts.

Pumakkal in Organic Waste Valorization and Circular Agriculture

Outside pineapple wastewater treatment, Pumakkal has also been applied to various organic wastes to produce nutrient-containing fertilizer materials. Reported applications include shrimp-pond waste, noodle-production waste, fish-market waste, rubber wastewater, catfish-pond water, chicken feathers, rice husks, pineapple peel and stem residues, and other organic materials (Abrori et al., 2022; Anggraeni et al., 2022; Ariyani et al., 2021; Gandini et al., 2022; Setyawan et al., 2022; Utomo et al., 2022; Yulita et al., 2024). These studies suggest that Pumakkal has potential as a fermenter or decomposer in waste-to-resource transformation. The examples of Pumakkal application in organic waste valorization are summarized in Table 3.

Table 3. Examples of Pumakkal application in organic waste valorization.

Waste type	**Main reported result**	**Meaning for circular agriculture**
Shrimp-pond liquid waste and sediment	Produced fertilizer material with N 1.3%, P 2.3%, K 2.3%, organic C 23%, C/N 29, pH 5–6, and micronutrients Fe, Cu, Zn, Mn, B, and Mo (Ariyani et al., 2021; Sutanto et al., 2024)	Shows the potential of shrimp-pond waste as an agricultural nutrient source
Noodle-production waste	P5/15-isolate treatment produced the best quality, with N+P+K reported to meet Indonesian standards (Gandini et al., 2022)	Shows the potential of food-industry waste as liquid fertilizer material
Fish-market waste	Pumakkal-based liquid fertilizer produced high N+P+K, and heavy metal and microorganism parameters were reported to meet standards (Utomo et al., 2022)	Shows the potential of fishery waste as a macronutrient source
Pineapple peel and stem	Pumakkal-based compost showed changes in physical and chemical compost quality (Setyawan et al., 2022)	Shows the potential of solid pineapple residues as compost material
Rubber wastewater, catfish-pond water, chicken feathers, rice husks, and other organic wastes	Produced fertilizer materials or organic products with certain nutrient contents (Abrori et al., 2022; Anggraeni et al., 2022; Yulita et al., 2024)	Shows Pumakkal flexibility in supporting waste-to-resource processes

The data summarized in Table 3 show that Pumakkal is not limited to pollutant reduction in pineapple wastewater. It has also been explored as a microbial agent for transforming organic residues into materials containing nitrogen, phosphorus, potassium, organic carbon, and micronutrients. From the perspective of circular agriculture, this role is important because organic waste can be repositioned from a disposal problem into a potential agricultural input. This principle

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is consistent with circular bioeconomy and waste-to-resource approaches that emphasize the reintegration of organic waste into productive systems (El-Ramady et al., 2022; Santos et al., 2024; Venkatesham et al., 2025).

Even so, the valorization evidence calls for caution. Each waste type has different organic composition, moisture content, nutrient content, contaminant risk, and fermentation behavior, so the quality of products generated from one waste type cannot be generalized to all other waste types. The term "fertilizer material" is more appropriate than "biofertilizer" unless the final product is proven to contain viable beneficial microorganisms and meets specific biofertilizer standards. The current evidence supports the potential of Pumakkal in producing nutrient-containing organic fertilizer materials, but it does not yet establish universal agronomic effectiveness across crops, soils, or field conditions.

Within a circular agriculture framework, Pumakkal contributes by linking pollutant reduction with resource recovery. This contribution may support reduced reliance on synthetic inputs in the long term, particularly in local agricultural systems with access to organic waste feedstocks, though this potential requires further field validation, including crop-response trials, fertilizer-quality standardization, contaminant assessment, microbial safety evaluation, and economic feasibility analysis. For this reason, Pumakkal should be positioned as a promising microbial platform for organic waste valorization rather than as a fully standardized agricultural input.

Relevance of Pumakkal to the Sustainable Development Goals and Contextual Biology Learning

The synthesis suggests that Pumakkal is relevant to selected Sustainable Development Goals, although the strength of evidence differs across goals. The strongest direct relevance is related to SDG 6 and SDG 12. Improvements in pH, biochemical oxygen demand, chemical oxygen demand, and total suspended solids are directly linked to SDG 6 on clean water and sanitation. The transformation of organic wastes into nutrient-containing fertilizer materials is directly linked to SDG 12 on responsible consumption and production. In contrast, the links to SDG 2 and SDG 4 are better read as downstream implications. The potential contribution to SDG 2 depends on further agronomic validation of Pumakkal-derived fertilizer materials, while the contribution to SDG 4 depends on the development and testing of Pumakkal-based learning resources.

Table 4. Mapping Pumakkal contributions to the Sustainable Development Goals.

SDGs	Research basis	Contribution	Level of evidence
SDG 6: Clean Water and Sanitation	Pumakkal improves pH and reduces BOD, COD, and	Supports reduction of water pollution from agroindustrial waste	Direct evidence from bioremediation data

	TSS in pineapple wastewater		
SDG 12: Responsible Consumption and Production	Pumakkal supports the transformation of organic waste into resources	Supports circular economy and waste-to-resource principles	Direct evidence from waste valorization studies
SDG 2: Zero Hunger	Pumakkal supports the use of organic waste as fertilizer material	Potentially supports sustainable agriculture through nutrient recovery	Downstream implication requiring agronomic validation
SDG 4: Quality Education	Pumakkal research outcomes can be developed as contextual biology learning resources	Supports learning in microbiology, environmental biotechnology, and sustainability	Downstream implication requiring educational validation

The educational dimension in this article is positioned as an implication rather than a primary research finding. Pumakkal has potential as a contextual biology learning resource because it connects microbiology, bioremediation, environmental pollution, local biotechnology, circular agriculture, and sustainability. Several Pumakkal-related studies have used research outcomes as teaching materials, student worksheets, or biology learning resources (Anggarawati et al., 2024; Anggraeni et al., 2022; Sidik et al., 2020; Yulita et al., 2024), yet this article does not claim that Pumakkal directly improves learning outcomes, scientific literacy, or twenty-first-century skills, because such claims require specific educational research designs.

The educational contribution of Pumakkal is thus best understood as contextual relevance rather than direct pedagogical effectiveness. If the educational dimension is to become the main focus of future work, it should be investigated using appropriate educational research designs, such as learning-material trials, pretest-posttest designs, scientific-literacy instruments, student-response analysis, or evaluation of science process skills. This distinction is important to keep the article focused on environmental biotechnology while acknowledging its potential educational value.

Overall, the available evidence positions Pumakkal as a local microbial innovation with three connected contributions. First, it functions as an indigenous bacterial consortium that improves pineapple wastewater quality under reported testing conditions. Second, it supports organic waste valorization by contributing to the conversion of several waste streams into nutrient-containing fertilizer materials. Third, it provides a contextual case for biology learning and sustainability education. Even so, broader implementation requires stronger molecular identification of bacterial isolates, biosafety evaluation, process standardization, field-scale validation, and long-term agronomic-effectiveness testing.

CONCLUSION

This study positions Pumakkal as a local microbial innovation developed from an indigenous bacterial consortium derived from pineapple wastewater. The synthesis shows that Pumakkal can improve pineapple wastewater quality under reported laboratory, pilot-scale, limited-scale, and ex situ testing conditions by increasing pH toward near-neutral values and reducing biochemical oxygen demand, chemical oxygen demand, and total suspended solids. Fish bioindicator observations further suggest that Pumakkal-bioremediated effluent has better relative biological compatibility than untreated pineapple wastewater, though this should be read as supportive bioindicator information rather than definitive proof of full ecological safety.

Beyond wastewater treatment, Pumakkal shows potential for organic waste valorization by supporting the conversion of several organic waste streams into nutrient-containing fertilizer materials. This role links pollutant reduction with resource recovery and places Pumakkal within a circular agriculture and waste-to-resource framework. The strongest evidence supports the relevance of Pumakkal to SDG 6 through wastewater quality improvement and SDG 12 through organic waste utilization. Its links to SDG 2 and SDG 4 are best read as downstream implications that require further agronomic and educational validation.

Overall, Pumakkal can be understood as a promising local microbial platform for pineapple wastewater bioremediation, organic waste valorization, and contextual sustainability learning. Even so, broader implementation requires stronger molecular identification of bacterial isolates, biosafety assessment, process standardization, field-scale validation, regulatory compliance evaluation, and long-term testing of agronomic effectiveness across different crops, soils, and environmental conditions.

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