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Original Article

Co-fermentation of pineapple and palm oil wastes by indigenous bacterial consortia for sustainable organic fertilizer production

Cofermentação de resíduos de abacaxi e óleo de palma por consórcios bacterianos indígenas para a produção sustentável de fertilizantes orgânicos

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Abstract

Agro-industrial wastes represent an abundant biomass resource that can be converted into value-added products through microbial bioconversion. This study evaluated the effectiveness of indigenous bacterial consortia with different levels of microbial diversity for improving the co-fermentation of pineapple processing waste and palm oil mill waste into organic fertilizers. Fifteen indigenous bacterial isolates were assembled into five consortium formulations (F1-F5) containing 3, 6, 9, 12, and 15 isolates, respectively. The consortia were applied to liquid and solid substrates of pineapple waste, palm oil mill waste, and their mixtures under a completely randomized design with three biological replicates. Fertilizer quality was assessed by determining total N + P_2O_5 + K_2O, organic carbon, C/N ratio, and pH. Increasing consortium diversity significantly improved nutrient enrichment and organic fertilizer quality ($P < 0.05$). The results showed that among the treatments, the F5 consortium consistently produced the highest nutrient contents, reaching 5.8% total N + P_2O_5 + K_2O in the mixed liquid substrate and 2.30% in the pineapple solid substrate. The same treatment also significantly increased organic carbon content, reduced the C/N ratio to 9-10, and stabilized pH at 6.0-6.4 compared with the uninoculated (control), indicating advanced organic matter decomposition and the production of mature, stable organic fertilizers that comply with Indonesian quality standards. These findings demonstrate that functionally diverse indigenous bacterial consortia enhance nutrient mineralization and organic matter stabilization during co-fermentation. This biological approach provides an environmentally sustainable strategy for recycling agro-industrial residues into nutrient-rich organic fertilizers, thereby supporting sustainable agriculture and the development of a circular bioeconomy.

Keywords: indigenous bacterial consortia, co-fermentation, agro-industrial waste, organic fertilizer, waste valorization.

Resumo

Resíduos agroindustriais representam um recurso abundante de biomassa que pode ser convertido em produtos de valor agregado por meio da bioconversão microbiana. Este estudo avaliou a eficácia de consórcios bacterianos autóctones com diferentes níveis de diversidade microbiana para melhorar a cofermentação de resíduos do processamento de abacaxi e resíduos de usinas de óleo de palma em fertilizantes orgânicos. Quinze isolados bacterianos autóctones foram reunidos em cinco formulações de consórcio (F1-F5), contendo 3, 6, 9, 12 e 15 isolados, respectivamente. Os consórcios foram aplicados a substratos líquidos e sólidos de resíduos de abacaxi, resíduos de usinas de óleo de palma e suas misturas, em delineamento inteiramente casualizado com três repetições biológicas. A qualidade do fertilizante foi avaliada pela determinação de N + P_2O_5 + K_2O total, carbono orgânico, relação C/N e pH. O aumento da diversidade do consórcio melhorou significativamente o enriquecimento de nutrientes e a qualidade do fertilizante orgânico ($P < 0,05$). Os resultados mostraram que, entre os tratamentos, o consórcio F5 produziu consistentemente os maiores teores de nutrientes, atingindo 5,8% de N + P_2O_5 + K_2O total no substrato líquido misto e 2,30% no substrato sólido de abacaxi. O mesmo tratamento também aumentou o teor de carbono orgânico, reduziu a relação C/N para 9-10 e estabilizou o pH entre 6,0 e 6,4, indicando decomposição avançada da matéria orgânica e produção de fertilizantes orgânicos maduros e estáveis, que atendem aos padrões de qualidade indonésios. Essas descobertas demonstram que consórcios bacterianos indígenas funcionalmente diversos aprimoram a mineralização de nutrientes e a estabilização da matéria orgânica durante a cofermentação. Essa abordagem biológica fornece uma estratégia ambientalmente sustentável para a reciclagem de resíduos agroindustriais em fertilizantes orgânicos ricos em nutrientes, apoiando, assim, a agricultura sustentável e o desenvolvimento de uma bioeconomia circular.

Palavras-chave: consórcios bacterianos indígenas, cofermentação, resíduos agroindustriais, fertilizante orgânico, valorização de resíduos.

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1. Introduction

The rapid expansion of agro-industrial activities has generated massive quantities of organic waste, creating significant environmental and sustainability challenges worldwide. Improper disposal of agro-industrial residues through open dumping, uncontrolled decomposition, or burning contributes to greenhouse gas emissions, contaminates surface and groundwater with high organic loads, and results in the inefficient use of valuable biomass resources that could otherwise be converted into bio-based products, renewable energy, or organic fertilizers (Chavan et al., 2022; Ravindran et al., 2021). In recent years, the sustainable management and valorization of agro-industrial waste have received increasing attention as essential strategies for mitigating environmental pollution while recovering energy, nutrients, and other value-added products from biomass resources. Such approaches are fundamental to the transition from a linear production system to a circular bioeconomy, in which agricultural residues are recycled into valuable products through environmentally sustainable biorefinery and biological conversion processes (Yaashikaa et al., 2022; Brandão et al., 2021). Consequently, effective agro-industrial waste valorization not only reduces greenhouse gas emissions and environmental degradation but also improves resource-use efficiency and supports sustainable agricultural and industrial development.

Recent advances in microbial biotechnology have demonstrated that multispecies microbial consortia generally outperform single microbial inoculants because of synergistic metabolic interactions, functional complementarity, and cooperative extracellular enzyme production. The diverse metabolic capabilities of microbial consortia enable the coordinated degradation of complex organic substrates, resulting in greater process stability, substrate utilization efficiency, and adaptability than monoculture inoculants (Greff et al., 2022; Zhou et al., 2024). During composting and biological waste conversion, such synergistic interactions accelerate the decomposition of carbohydrates, proteins, lipids, cellulose, hemicellulose, and lignin, thereby enhancing nutrient mineralization, promoting humification, shortening compost maturation time, and improving the quality of the final organic fertilizer (Nigussie et al., 2021; Duan et al., 2024). Furthermore, indigenous microbial consortia are often better adapted to local substrates and environmental conditions than commercially available inoculants because they have evolved under the physicochemical conditions of the target biomass. This ecological adaptation improves microbial survival, enzymatic activity, and degradation efficiency, making indigenous microbial consortia particularly attractive for sustainable biomass valorization and agro-industrial waste bioconversion (Greff et al., 2022; Zhou et al., 2024). The use of locally adapted microbial consortia therefore represents a promising strategy for improving the efficiency, scalability, and environmental sustainability of organic waste recycling.

Although numerous studies have investigated the composting and microbial fermentation of individual agricultural residues, including palm oil mill wastes and other lignocellulosic biomass, relatively few studies have examined the co-fermentation of pineapple and palm oil residues using indigenous multispecies bacterial consortia (Greff et al., 2022; Rupani et al., 2022). Pineapple waste contains high levels of organic matter, readily biodegradable carbohydrates, soluble sugars, minerals, and other essential nutrients, making it an excellent substrate for microbial fermentation and organic fertilizer production. In contrast, palm oil empty fruit bunches are lignocellulosic biomass predominantly composed of cellulose, hemicellulose, and lignin, which provide structural rigidity but also make the material relatively resistant to natural biodegradation, thereby requiring microbial or biological pretreatment to accelerate decomposition (Khalid et al., 2019; Supriatna et al., 2022; Sarangi et al., 2023; Paz-Arteaga et al., 2024). These complementary physicochemical characteristics suggest that combining pineapple waste with palm oil residues could improve the biodegradation process by balancing readily degradable carbon sources with more recalcitrant lignocellulosic components, thereby creating favorable conditions for synergistic microbial activity during co-fermentation. However, most previous research has focused on optimizing microbial inoculants, composting conditions, or the treatment of single waste streams, whereas the co-fermentation of complementary agro-industrial substrates using indigenous bacterial consortia remains insufficiently explored (Supriatna et al., 2022; Duan et al., 2024). Furthermore, little information is available regarding the performance of their capacity to consistently produce organic fertilizers that comply with national quality standards. These knowledge gaps limit the large-scale implementation and commercialization of indigenous microbial technologies for sustainable agro-industrial waste valorization and circular bioeconomy applications, despite increasing evidence that microbial consortia offer superior efficiency, robustness, and adaptability for biomass conversion compared with conventional inoculation strategies (Zhou et al., 2024).

To address these gaps, this study introduces a novel indigenous bacterial consortium composed of multifunctional hydrolytic bacteria capable of degrading carbohydrate-, protein-, lipid-, and lignocellulose-rich agro-industrial residues through synergistic microbial interactions. Previous studies have demonstrated the effectiveness of indigenous bacterial consortium in accelerating the biodegradation of agricultural, aquaculture, and domestic organic wastes (Seenivasagan and Babalola, 2021; Cao et al., 2022; Kurniawan et al., 2022; Sari et al., 2022; Zhou et al., 2024). Building upon these findings, the present study evaluated, for the first time, the effectiveness of the bacterial consortia in the co-fermentation of pineapple and palm oil wastes under laboratory conditions. This work provides a practical proof of concept for converting two major agro-industrial wastes into high-quality organic fertilizers using locally adapted bacterial consortia, thereby supporting sustainable agriculture, resource recovery, and the circular bioeconomy.

2. Materials and Methods

2.1. Study site

This laboratory study was conducted at the Experimental Complex of Universitas Muhammadiyah Metro

(5°7′13.824″S, 105°19′47.529″E), Lampung Province, Indonesia from September 2023 to March 2024. Pineapple liquid and solid wastes were collected from local pineapple processing industries, while palm oil empty fruit bunches (EFB) and palm oil liquid waste were obtained from a local palm oil mill. All waste materials were transported to the laboratory and stored at 4°C prior to use.

2.2. Characteristics of potentially decomposing bacteria isolates

Fresh pineapple waste (250 mL) was aseptically collected and used as the source of indigenous decomposing bacteria. The samples were enriched in nutrient broth under aerobic conditions to promote the growth of metabolically active microorganisms capable of degrading organic substrates, as commonly applied for the isolation of efficient decomposers from agro-industrial wastes (Wei et al., 2018; Meng et al., 2019).

The enriched cultures were screened for hydrolytic activity against carbohydrates, proteins, and lipids. Purified isolates were incubated in liquid nutrient medium using a 500 mL bioreactor for 24 h, and hydrolysis indices were determined on selective media containing starch, skim milk, and tributyrin. Isolates showing high hydrolytic activity were selected as potential decomposing bacteria because extracellular hydrolytic enzymes play a key role in accelerating organic matter decomposition during composting and co-fermentation (Awasthi et al., 2022; Wang et al., 2024; Sharma et al., 2025).

Selected isolates were identified using the Microbact™ 12A/12B/24E Identification Kits based on their biochemical characteristics, including carbohydrate utilization and enzymatic reactions. The identification profiles were interpreted according to Bergey's Manual of Determinative Bacteriology (Holt et al., 2000), and bacterial nomenclature was verified using the current taxonomy published in the International Journal of Systematic and Evolutionary Microbiology (IJSEM) and the List of Prokaryotic names with Standing in Nomenclature (LPSN), which provide the accepted classification and nomenclature of prokaryotes (Parte et al., 2020).

2.3. Preparation of indigenous bacterial consortia

Five indigenous bacterial consortium formulations (F1-F5) were prepared containing 3, 6, 9, 12, and 15 bacterial isolates, respectively, to evaluate the effect of increasing bacterial diversity on the co-fermentation process. Each bacterial isolate was cultivated separately in sterile Nutrient Broth (NB) medium and incubated at 30°C for 24 h under continuous shaking at 150 rpm, conditions commonly employed to obtain actively growing bacterial cultures with high metabolic activity (Bai et al., 2015). Following incubation, the bacterial suspensions were standardized to approximately 10^8 CFU mL^{-1} by adjusting the optical density at 600 nm (OD600) using a spectrophotometer, a widely accepted approach for obtaining uniform inoculum densities in microbial inoculation experiments (Stevenson et al., 2016; Hall et al., 2014). Equal volumes of each standardized bacterial suspension were then mixed aseptically to produce consortium formulations with identical contributions from each constituent strain, thereby minimizing variations in initial cell abundance and allowing the evaluation of synergistic interactions among bacterial members during co-fermentation (Che et al., 2019; Lin et al., 2022). The prepared bacterial consortia were subsequently used as bioactivators in the co-fermentation experiments.

2.4. Co-fermentation experiment

The performance of five indigenous bacterial consortium formulations (F1-F5) was evaluated, with an uninoculated treatment serving as the control. Treatments were arranged in a Completely Randomized Design (CRD) with three independent biological replicates, and each biological replicate was analyzed in triplicate technical measurements for microbiological and physicochemical parameters. Each experimental unit consisted of an individual fermentation flask containing the designated bacterial consortium and growth medium.

Co-fermentation was performed using pineapple liquid waste, pineapple solid waste, palm oil empty fruit bunches (EFB), and palm oil mill effluent (POME). The substrates were mixed at predetermined proportions and inoculated with the indigenous bacterial consortia at 10% (v/w). Combining agro-industrial wastes with selected microbial consortia enhances organic matter degradation, nutrient mineralization, and compost quality by providing complementary substrates and accelerating microbial activity (Zhou et al., 2025; Salih et al., 2026).

Fermentation was conducted for 30 days. Solid organic fertilizer was produced by aerobic composting in aerated containers with turning every three days, maintaining moisture at 55-65% and temperature between 30 and 45°C, conditions favorable for efficient biodegradation (Bernal et al., 2009; Cheah et al., 2023). Liquid organic fertilizer was produced by anaerobic fermentation in closed bioreactors equipped with gas-release valves. Experimental units were randomly allocated, and their positions were periodically rearranged whenever feasible to minimize positional effects.

2.5. Chemical analysis of organic fertilizer

Samples of liquid and solid organic fertilizers were collected at the end of the fermentation process for chemical analysis. Total nitrogen (N) was determined using the Kjeldahl digestion and distillation method following the procedures described by Bremner (1996). Phosphorus (P) concentration was determined colorimetrically using a UV-Vis spectrophotometer based on the molybdenum blue method, while potassium (K) concentration was measured using a flame photometer according to the standard procedures outlined by Jones Junior (2001). Organic carbon (C) content was determined using the Walkley-Black wet oxidation method as described by Nelson and Sommers (1996). The pH of the fertilizer samples was measured using a calibrated digital pH meter in accordance with standard analytical procedures (Jones Junior, 2001). The C/N ratio was subsequently calculated from the measured values of total organic carbon and total nitrogen.

2.6. Statistical analysis

Experimental data were analyzed using one-way analysis of variance (ANOVA) with IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Prior to ANOVA, the

assumptions of normality and homogeneity of variance were evaluated. The normality of residuals was assessed using the Shapiro-Wilk test, while the homogeneity of variance among treatments was verified using Levene's test. When these assumptions were satisfied ($P > 0.05$), ANOVA was performed to determine the effect of bacterial consortium formulations on the measured variables. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at a 5% significance level ($P < 0.05$) (Steel and Torrie, 1997). All experiments were conducted using three independent biological replicates, and each biological replicate was analyzed in triplicate technical measurements.

3. Results and Discussion

3.1. Isolation, identification, and formulation of bacterial consortia

In the present study, isolation and identification of bacteria from pineapple waste yielded 15 indigenous bacterial isolates belonging predominantly to the genus *Bacillus*, together with representatives of *Acinetobacter*, *Klebsiella*, *Pseudomonas*, and *Actinobacillus* (Table 1). The predominance of *Bacillus* spp. suggests that pineapple waste is a suitable habitat for hydrolytic bacteria because members of this genus are well known for producing extracellular enzymes involved in the degradation of complex organic materials, including cellulose, starch, proteins, and lipids (Ravindran et al., 2018; Kumar et al., 2026; Cosme-Perlaza et al., 2026; Wani et al., 2026).

Based on their hydrolytic characteristics, the fifteen isolates were assembled into five indigenous bacterial consortium formulations (F1-F5) with increasing numbers of isolates and complementary enzymatic functions (Table 2). The consortium complexity increased from F1, containing three fat-degrading isolates, to F5, comprising all fifteen isolates capable of degrading proteins, starch, and fats simultaneously. This progressive increase in functional diversity was intended to enhance substrate decomposition through synergistic microbial interactions. Notably, previous studies have shown that microbial consortia with complementary metabolic capabilities generally outperform single strains by broadening substrate utilization and improving biodegradation efficiency during organic waste fermentation (Seenivasagan and Babalola, 2021; Lü et al., 2024; Zhang and Zhang, 2022; Cao et al., 2022; Cosme-Perlaza et al., 2026).

Because one of the isolates was identified as *Pseudomonas pseudomallei* (currently classified as *Burkholderia pseudomallei*), biosafety considerations should be acknowledged due to the pathogenic potential of this species as the causative agent of melioidosis. All isolation, characterization, and consortium formulation procedures in the present study were conducted under appropriate institutional laboratory biosafety practices to ensure the safe handling of bacterial cultures and to minimize potential exposure risks. Furthermore, the bacterial consortia were developed exclusively for controlled laboratory-scale fermentation experiments and were not intended for direct environmental release. Previous studies have emphasized that accurate taxonomic identification together with appropriate biosafety measures are essential when working with environmental bacterial isolates, particularly members of the genus Burkholderia, to ensure laboratory safety and regulatory compliance (Birnie et al., 2019; Wiersinga et al., 2018).

Table 1. Bacterial isolates obtained from pineapple waste and their taxonomic identification.

Isolate number	Species
1.	*Bacillus licheniformis*
2.	*Bacillus cereus*
3.	*Bacillus cereus*
4.	*Bacillus subtilis*
5.	*Bacillus cereus*
6.	*Bacillus subtilis*
7.	*Acinetobacter baummanii*
8.	*Acinetobacter baummanii*
9.	*Klebsiella oxitoca*
10.	*Bacillus subtilis*
11.	*Bacillus cereus*
12.	*Pseudomonas pseudomallei*
13.	*Actinobacillus iwoffii*
14.	*Actinobacillus iwoffii*
15.	*Bacillus firmus*

3.1.1. Changes in N + P_2O_5 + K_2O content of liquid waste

The indigenous bacterial consortia significantly affected the total N + P_2O_5 + K_2O content of the liquid organic fertilizers produced from pineapple liquid waste (PiLW), palm oil liquid waste (PaLW), and their 1:1 mixture (PiPaLW) ($P < 0.05$; Table 3). In all three substrates, the uninoculated control (F0) had the lowest nutrient content, whereas inoculation with increasingly diverse bacterial consortia generally resulted in greater nutrient enrichment. This finding indicates that microbial inoculation accelerated the transformation of organically bound nutrients into more measurable mineral and soluble forms through organic matter degradation and nutrient mineralization (Geisseler et al., 2021; Zhou et al., 2023; Singh et al., 2023).

In PiLW, the total N + P_2O_5 + K_2O content increased significantly from 2.1% in F0 to 3.1%, 4.2%, and 5.1% in F1, F2, and F3, respectively. The highest value of 5.2% was obtained with both F4 and F5, corresponding to an increase of 147.6%, or approximately 2.5-fold, relative to the control. However, F3, F4, and F5 shared the same statistical group and therefore did not differ significantly from one another. This result suggests that the readily fermentable sugars, soluble carbohydrates, and organic acids supplied by pineapple waste supported rapid microbial growth and nutrient transformation even in the less diverse consortia. Consequently, increasing consortium size beyond nine isolates provided little additional improvement in PiLW,

Table 2. Indigenous Bacteria Consortium Formula obtained from pineapple waste and their hydrolysis ability.

Bacterial Consortium and Number of Isolates	Bacterial Isolates	Hydrolysis Capability
F1 (Three isolates)	Isolate 2, 3, 5	Fat degraders
F2 (Six isolates)	Isolate 4, 5, 6, 7, 12, 14	Amylum degraders
F3 (Nine isolates)	Isolate 1, 2, 3, 8, 10, 11, 12, 14, 15	Protein degraders
F4 (Twelve isolates)	Isolate 1, 2, 3, 7, 8, 9, 10, 11, 12, 13, 14, 15	Protein and amylum degraders
F5 (Fifteen isolates)	Isolate 1 to 15	Proteins, amylum, and fats degraders

Table 3. The N + P_2O_5 + K_2O contents in the liquid organic fertilizer produced from pineapple liquid waste, palm oil liquid waste, and pineapple liquid + palm oil liquid wastes.

Bacterial Consortium	PiLW	PaLW (%)	PiPaLW
F0 (control)	2.1 a	1.1 a	2.1 a*
F1 (Three isolates)	3.1 b	1.5 b	3.0 b
F2 (Six isolates)	4.2 c	3.0 c	4.3 c
F3 (Nine isolates)	5.1 d	2.5 d	5.1 d
F4 (Twelve isolates)	5.2 d	4.3 e	5.5 e
F5 (Fifteen isolates)	5.2 d	4.6 f	5.8 f
CV (%)	1.92	4.23	2.42

*Numbers with identical letters within the same column are not different according to the DMRT at $P < 0.05$. PiLW = pineapple liquid waste; PaLW = palm oil liquid waste; PiPaLW = pineapple liquid waste + palm oil liquid waste mixed at a 1:1 volume ratio (v/v). For Liquid Organic Fertilizer, according to the Decree of the Minister of Agriculture of the Republic of Indonesia No. 261 of 2019, concerning the Minimum Technical Requirements, the standard of N + P_2O_5 + K_2O content is 2-6% (Indonesia, 2019).

possibly because the easily degradable carbon pool had already been efficiently utilized or had become limiting.

A stronger response to consortium diversity was observed in PaLW. The total nutrient content increased from 1.1% in F0 to 4.6% in F5, representing a 318.2% increase, or approximately 4.2-fold enrichment. F5 was significantly higher than F4 (4.3%), F3 (2.5%), F2 (3.0%), F1 (1.5%), and F0, as shown by the different DMRT letters. The superior response of PaLW to F5 may be associated with the more complex composition of palm oil processing waste, including lipid-rich compounds and less readily degradable organic materials. The fifteen-isolate consortium contained bacteria capable of degrading proteins, starch, and fats and therefore provided a broader range of complementary extracellular enzymes than the smaller consortia. Lipases, proteases, amylases, and other hydrolytic enzymes may have converted complex organic compounds into simpler substrates that could be used by other members of the consortium. Such cross-feeding can maintain microbial metabolism by allowing the products released by one bacterial species to serve as carbon, energy, or nutrient sources for another species, thereby enhancing mineralization and internal nutrient cycling (Singh et al., 2023).

The PiPaLW mixture produced the highest nutrient concentration among the evaluated liquid substrates. Total N + P_2O_5 + K_2O increased significantly from 2.1% in F0 to 3.0%, 4.3%, 5.1%, 5.5%, and 5.8% in F1, F2, F3, F4, and F5, respectively. Thus, F5 increased nutrient content by 176.2%, equivalent to approximately 2.8 times the control value, and was significantly higher than all other treatments. It was also 5.5% higher than F4, demonstrating that the additional isolates in F5 made a statistically detectable contribution to nutrient enrichment in the mixed substrate. The improved performance of PiPaLW was probably related to substrate complementarity. Pineapple waste supplied readily available sugars and soluble carbon compounds that could support initial bacterial growth, whereas palm oil waste supplied lipids and more complex organic compounds that sustained microbial activity during subsequent fermentation stages. Mixing the wastes may also have produced a more balanced carbon-to-nitrogen supply than either substrate alone, thereby preventing severe carbon or nutrient limitation and supporting a wider range of microbial metabolic functions (Rahman et al., 2022).

The liquid nature and high moisture content of the substrates may have further promoted microbial activity by facilitating nutrient diffusion, enzyme-substrate contact, and the movement of intermediate metabolites among bacterial cells. These conditions would be particularly advantageous for the F5 consortium because its greater functional diversity allowed different bacterial groups to occupy complementary metabolic roles. Synergistic interactions among the fifteen isolates likely enhanced the sequential degradation of carbohydrates, proteins, and lipid-rich compounds, while cross-feeding reduced the accumulation of inhibitory intermediates and improved nutrient recycling. Consequently, a greater proportion of organically bound N, P, and K was released or retained in the fermented material.

In short, the statistical results demonstrate that the effectiveness of increasing consortium diversity depended on substrate composition. F5 did not significantly outperform F3 or F4 in the relatively easily degradable PiLW, but it produced significantly higher nutrient contents than all smaller consortia in PaLW and PiPaLW. Its superior performance in the more chemically diverse substrates can therefore be attributed to complementary extracellular enzyme production, synergistic microbial interactions, cross-feeding, enhanced mineralization, and more efficient nutrient cycling. These results support previous findings that functionally diverse microbial consortia can improve the biodegradation of agro-industrial wastes and increase the nutrient value of the resulting organic fertilizers (Zhao et al., 2022; Zhou et al., 2024).

3.1.2. Changes in C, C/N, and pH of liquid waste

The indigenous bacterial consortia significantly affected the C-organic content, C/N ratio, and pH of the liquid organic fertilizers produced from pineapple liquid waste (PiLW), palm oil liquid waste (PaLW), and their mixture (PiPaLW) ($P < 0.05$; Table 4). In general, increasing consortium diversity improved all three parameters, with F5 producing the highest C-organic content, the lowest C/N ratio, and the highest pH.

C-organic content increased significantly following bacterial inoculation. In PiLW, it increased from 32% in F0 to 36% in F5 (12.5% increase), although F3-F5 were statistically similar, indicating that intermediate consortia were already sufficient to utilize the readily degradable sugars and soluble carbon present in pineapple waste. In PaLW, C-organic increased from 28% to 32% (14.3%), with F5 significantly higher than the control but comparable to F3. The strongest response occurred in PiPaLW, where C-organic increased from 27% in F0 to 37% in F5 (37.0% increase), and F5 formed a distinct statistical group, demonstrating the highest carbon conversion efficiency.

The superior performance of F5 was likely due to synergistic interactions among the fifteen bacterial isolates. Their complementary extracellular enzymes enhanced the degradation of carbohydrates, proteins, and lipid-rich compounds, while cross-feeding enabled metabolites released by one species to be utilized by others. The mixed PiPaLW substrate further promoted microbial activity by combining readily fermentable sugars from pineapple waste with lipid-rich compounds from palm oil waste, providing a more balanced supply of carbon, nutrients, and moisture that supported sustained microbial metabolism and efficient nutrient cycling (Awasthi et al., 2021; Varjani et al., 2022; Cheah et al., 2023).

The C/N ratio decreased significantly in all substrates, indicating enhanced organic matter stabilization. In PiLW, the ratio declined from 19 to 10 (47.4%), while in PaLW it decreased from 20 to 10 (50.0%). The greatest reduction occurred in PiPaLW, where the C/N ratio decreased from 19 to 9 (52.6%). Although F5 produced the lowest numerical values, F2-F5 generally belonged to the same statistical group, indicating that most of the reduction occurred after bacterial inoculation rather than with increasing consortium size. These reductions resulted from accelerated carbon degradation combined with nitrogen mineralization, leading to a more balanced C/N ratio characteristic of mature organic fertilizers.

The pH of all liquid wastes increased markedly during fermentation. PiLW increased from 3.0 to 6.3, PaLW from 4.0 to 6.3, and PiPaLW from 3.0 to 6.4. In PiPaLW, F3-F5 showed statistically similar pH values, whereas all inoculated treatments were significantly higher than the control. The increase in pH was associated with microbial degradation of organic acids and ammonification during protein decomposition. The metabolically diverse F5 consortium likely accelerated these processes through complementary enzyme production and cross-feeding, preventing the accumulation of acidic intermediates and promoting more efficient mineralization (Varjani et al., 2022; Li et al., 2024; Dey et al., 2025).

In summary, the effectiveness of F5 depended on substrate composition. Its advantage was most

Table 4. The values of C-organic, C/N ratio, and pH in the liquid organic fertilizer produced from pineapple liquid waste, palm oil liquid waste, and pineapple liquid waste + palm oil liquid waste.

Bacterial Consortium	C-organic			C/N ratio			pH		
	PiLW	PaLW	PiPaLW	PiLW	PaLW	PiPaLW	PiLW	PaLW	PiPaLW
	---------- % ----------								
F0	32 a	28 a	27 a	19 c	20 b	19 c	3.0 a	4.0 c	3.0 a*
F1	33 ab	31 ab	30 ab	15 b	13 a	15 b	5.5 b	5.7 b	4.5 b
F2	34 bc	30 ab	30 ab	12 ab	12 a	11 a	5.8 bc	5.8 b	5.1 b
F3	35 c	32 b	31 cb	11 a	10 a	10 a	6.1 bc	6.1 ab	6.0 c
F4	36 c	31 ab	33 c	9 a	10 a	10 a	6.1 bc	6.1 ab	6.1 c
F5	36 c	32 b	37 d	10 a	10 a	9 a	6.3 c	6.3 a	6.4 c
CV (%)	2.12	4.25	3.26	9.17	9.14	10.19	3.90	2.78	5.03

*Numbers with identical letters within the same column are not different according to the DMRT at $P < 0.05$. F0 = (Control); F1 = (Three isolates); F2 = (Six isolates); F3 = (Nine isolates); F4 = (Twelve isolates); F5 = (Fifteen isolates); PiLW = pineapple liquid waste; PaLW = palm oil liquid waste; PiPaLW = pineapple liquid waste + palm oil liquid waste mixed at a 1:1 volume ratio (v/v). For Liquid Organic Fertilizer, according to the Decree of the Minister of Agriculture of the Republic of Indonesia No. 261 of 2019, concerning the Minimum Technical Requirements, the standards of minimum C-organic content are 10% and pH 4-9 (Indonesia, 2019).

evident in the mixed PiPaLW substrate, where nutrient complementarity between pineapple and palm oil wastes supported greater microbial diversity and metabolism. Pineapple waste supplied easily degradable carbon, whereas palm oil waste provided more complex lipid-rich substrates, allowing the diverse bacterial community to maximize organic matter degradation, nutrient cycling, and stabilization. Consequently, F5 produced C-organic contents of 32-37%, C/N ratios of 9-10, and pH values of 6.3-6.4, indicating well-stabilized liquid organic fertilizers suitable for agricultural application (Bernal et al., 2009; Li et al., 2024; Salih et al., 2026).

3.1.3. Changes in N + P_2O_5 + K_2O content in solid waste

For solid waste, the results in Table 5 shows that indigenous bacterial consortia significantly increased ($P < 0.05$) the total N + P_2O_5 + K_2O content of solid organic fertilizers produced from pineapple solid waste (PiSW), palm oil solid waste (PaSW), and their co-fermented mixture (PiPaSW). In all substrates, the uninoculated control (F0) produced the lowest nutrient content, whereas nutrient enrichment generally increased with consortium diversity. This trend indicates that increasing bacterial diversity enhanced organic matter decomposition, nutrient mineralization, and nutrient retention during fermentation (Nigussie et al., 2021).

The greatest response occurred in PiSW, where total N + P_2O_5 + K_2O increased significantly from 0.70% in F0 to 2.30% in F5, representing a 228.6% increase (3.3-fold). In PiPaSW, nutrient content increased from 0.44% to 2.09% (375.0%; 4.8-fold), whereas PaSW increased from 0.45% to 1.28% (184.4%; 2.8-fold). According to the DMRT results (Table 5), F5 consistently belonged to the highest statistical group and produced significantly greater nutrient contents than the control and most lower-diversity consortia, confirming that the addition of bacterial isolates substantially improved nutrient recovery during composting.

The superior performance of F5 can be attributed to synergistic microbial interactions among the fifteen indigenous isolates. Greater microbial diversity likely increased the production of complementary extracellular enzymes, including cellulases, hemicellulases, proteases, amylases, phosphatases, and lipases, enabling more efficient degradation of cellulose, hemicellulose, proteins, and other complex organic compounds. The hydrolysis products generated by one bacterial species could subsequently serve as carbon and energy sources for other species through cross-feeding, thereby sustaining microbial activity, accelerating mineralization, improving nutrient cycling, and reducing nutrient losses throughout the composting process (Greff et al., 2022; Lü et al., 2024).

Differences among substrates were closely related to their chemical composition. Pineapple residues contain abundant soluble sugars and readily degradable carbohydrates that rapidly stimulate microbial growth and nutrient mineralization, whereas palm oil residues contain more lignocellulosic materials that decompose more slowly. Consequently, PiSW showed greater nutrient enrichment than PaSW. In contrast, the co-fermented substrate (PiPaSW) benefited from substrate complementarity, where readily available carbon from pineapple waste supported rapid microbial establishment, while structural carbohydrates and residual lipid-rich components in palm oil waste sustained microbial metabolism during later stages of decomposition. The mixed substrate also provided a more balanced carbon supply, moisture conditions, and nutrient availability, creating favorable conditions for diverse microbial populations and more efficient nutrient transformation (Thien et al., 2021; Zziwa et al., 2021).

In general, the results demonstrate that increasing consortium diversity improved nutrient enrichment, although its effectiveness depended on substrate characteristics. The chemically diverse PiPaSW substrate showed the greatest proportional improvement, indicating that functionally diverse bacterial communities are particularly effective when multiple carbon sources are available. Through complementary metabolic functions, cross-feeding, enhanced mineralization, and efficient nutrient cycling, the F5 consortium consistently produced

Table 5. The N + P_2O_5 + K_2O contents in the solid organic fertilizer produced from pineapple solid waste, palm oil solid waste, and pineapple solid waste + palm oil solid waste.

Bacterial Consortium	PiSW	PaSW	PiPaSW
	---------- % ----------		
F0	0.7 a	0.45 a	0.44 a*
F1	1.2 a	1.01 b	1.05 b
F2	1.6 b	1.15 b	1.26 b
F3	1.7 b	1.02 bc	1.21 b
F4	1.8 b	1.37 c	1.66 c
F5	2.3 c	1.28 bc	2.09 d
CV (%)	6.08	9.61	9.63

*Numbers with identical letters within the same column are not different according to the DMRT at $P < 0.05$. F0 = (Control); F1 = (Three isolates); F2 = (Six isolates); F3 = (Nine isolates); F4 = (Twelve isolates); F5 = (Fifteen isolates); PiSW = pineapple solid waste; PaSW = palm oil solid waste; PiPaSW = pineapple solid waste + palm oil solid waste mixed at a 1:1 weight ratio (w/w). For Solid Organic Fertilizer, according to the Decree of the Minister of Agriculture of the Republic of Indonesia No. 261 of 2019, concerning the Minimum Technical Requirements, the standards of a minimum total N + P_2O_5 + K_2O content is 2% (Indonesia, 2019).

the highest N + P_2O_5 + K_2O contents, confirming that diverse indigenous bacterial consortia are an effective strategy for converting pineapple and palm oil processing wastes into nutrient-rich solid organic fertilizers (Geisseler et al., 2021; Ravindran et al., 2021; Chegini et al., 2026; Li et al., 2026).

3.1.4. Changes in C, C/N, and pH of solid waste

The results in Table 6 shows that the indigenous bacterial consortia significantly influenced ($P < 0.05$) the C-organic content, C/N ratio, and pH of the solid organic fertilizers produced from pineapple solid waste (PiSW), palm oil solid waste (PaSW), and their co-fermented mixture (PiPaSW) (Table 6). In all substrates, C-organic content increased, whereas the C/N ratio decreased and pH approached neutrality as consortium diversity increased. The F5 consortium consistently produced the highest C-organic contents (31%, 31%, and 27% for PiSW, PaSW, and PiPaSW, respectively), the lowest C/N ratios (10-12), and pH values around 6.0, indicating superior compost stabilization. According to the DMRT results, F5 belonged to the highest statistical group for most parameters, demonstrating that increasing microbial diversity significantly improved compost quality compared with the uninoculated control and lower-diversity consortia.

The superior performance of F5 can be attributed to synergistic interactions among the fifteen indigenous bacterial isolates. The diverse consortium likely produced complementary extracellular enzymes, including cellulases, hemicellulases, proteases, amylases, and lipases, which accelerated the degradation of cellulose, hemicellulose, proteins, and other complex organic compounds. The hydrolysis products released by one bacterial species could subsequently serve as carbon and energy sources for other members through cross-feeding, thereby sustaining microbial activity, enhancing mineralization, improving nutrient cycling, and promoting the formation of stabilized organic matter (Nigussie et al., 2021; Greff et al., 2022; Lü et al., 2024).

Substrate composition also contributed to the observed responses. Pineapple residues contain abundant soluble sugars and readily degradable carbohydrates that support rapid microbial growth, whereas palm oil residues are richer in lignocellulosic materials and residual lipid-containing compounds that require a broader range of degradative enzymes. Co-fermentation of the two substrates provided complementary carbon sources together with more balanced nutrient availability and favorable moisture conditions, allowing the metabolically diverse F5 consortium to maintain microbial activity throughout the fermentation process. This substrate complementarity explains the consistently improved stabilization observed in the mixed substrate compared with individual wastes (Awasthi et al., 2021; Cheah et al., 2023).

The marked reduction in the C/N ratio from 20-21 in the control to 10-12 in F5 represents approximately a 43-52% decrease, indicating substantial decomposition of carbon-rich materials and enhanced nitrogen mineralization. Lower C/N ratios are widely recognized as indicators of compost maturity because they reflect efficient carbon utilization while conserving nitrogen in more stable forms. Likewise, pH increased from approximately 3.0 in the control to about 6.0 in F5, demonstrating effective degradation of organic acids and increased ammonification during composting. The near-neutral pH provides a more favorable environment for microbial metabolism, enzyme activity, and nutrient availability, further promoting compost stabilization (Awasthi et al., 2020; Li et al., 2026).

In this study, the statistical and biological evidence demonstrates that increasing consortium diversity enhanced the physicochemical quality of the solid organic fertilizers, although the magnitude of improvement depended on substrate composition. Through complementary enzyme production, synergistic microbial interactions, cross-feeding, enhanced mineralization, and efficient nutrient cycling, the F5 consortium consistently produced mature organic fertilizers characterized by higher C-organic

Table 6. The values of C-organic, C/N ratio, and pH in the solid organic fertilizer produced from pineapple solid waste, palm oil solid waste, and pineapple solid waste + palm oil solid waste.

Treatment	C-organik			C/N ratio			pH		
	PiSW*	PaSW*	PiPaSW*	PiSW*	PaSW*	PiPaSW*	PiSW*	PaSW*	PiPaSW*
	---------- % ----------								
F0	16 a	25 a	21 a	25 c	20 c	21 c	3 a	3 a	3 a
F1	28 a	27 ab	23 ab	20 b	15 b	17 b	3 a	4 b	4 b
F2	27 a	27 ab	25 ab	18 b	13 b	15 b	4 b	4 b	4 b
F3	30 a	30 ab	26 ab	16 ab	14 b	11 a	5 c	5 c	5 c
F4	30 a	30 b	26 ab	15 a	11 ab	10 a	5 c	6 d	5 c
F5	31 b	31 b	27 b	12 a	11 a	10 a	6 d	6 d	6 d
CV (%)	5.30	6.51	9.19	9.20	10.72	10.10	4.79	10.77	4.96

*Numbers with identical letters within the same column are not different according to the DMRT at $P < 0.05$. F0 = (Control); F1 = (Three isolates); F2 = (Six isolates); F3 = (Nine isolates); F4 = (Twelve isolates); F5 = (Fifteen isolates); PiSW = pineapple solid waste; PaSW = palm oil solid waste; PiPaSW = pineapple solid waste + palm oil solid waste mixed at a 1:1 weight ratio (w/w). For Solid Organic Fertilizer, according to the Decree of the Minister of Agriculture of the Republic of Indonesia No. 261 of 2019, concerning the Minimum Technical Requirements, the standards of minimum C-organic content are 15%, C/N ratio ≤ 25, and pH 4-9 (Indonesia, 2019).

content, lower C/N ratios, and near-neutral pH. The C/N ratios of 10-12 and pH around 6.0 are consistent with the characteristics of stable, mature organic fertilizers, indicating reduced phytotoxicity and improved suitability for agricultural application (Bernal et al., 2009; Awasthi et al., 2020).

3.2. Implications for sustainable agriculture, circular bioeconomy, and policy

The present study demonstrates that indigenous bacterial consortia, particularly the F5 consortium, can effectively transform pineapple and palm oil processing wastes into high-quality organic fertilizers with enhanced nutrient content and favorable physicochemical properties. These findings have important implications for sustainable agriculture because they provide an environmentally friendly alternative for recycling agro-industrial residues into valuable agricultural inputs. By accelerating organic matter decomposition and nutrient mineralization, the indigenous bacterial consortium promotes nutrient recycling, improves the efficiency of biomass utilization, and reduces dependence on inorganic fertilizers. The application of such biologically produced organic fertilizers has the potential to improve soil organic matter, enhance microbial activity, and support long-term soil fertility, which are fundamental principles of sustainable agricultural production systems (Salih et al., 2026; Chegini et al., 2026).

From a circular bioeconomy perspective, this study demonstrates an effective strategy for converting agricultural waste streams into value-added biofertilizers rather than treating them as disposal problems. Pineapple and palm oil processing industries generate substantial quantities of organic residues that are often underutilized or disposed of through environmentally undesirable practices. The successful co-fermentation of these wastes using indigenous microorganisms illustrates how biological technologies can close nutrient loops by returning carbon and plant nutrients to agricultural soils. Such waste valorization contributes to resource efficiency, reduces environmental pollution, lowers greenhouse gas emissions associated with waste accumulation, and supports the transition toward circular agricultural production systems in which biological resources are continuously recycled (Perwez and Al Asheh, 2024; Chegini et al., 2026).

In the current study, an important finding that deserves particular emphasis is that the F5 consortium consistently produced solid organic fertilizers with C/N ratios of approximately 10-12 and pH values around 6.0. These values are widely recognized as indicators of mature and stable compost, reflecting advanced organic matter stabilization, reduced phytotoxicity, and efficient microbial decomposition. A C/N ratio within this range indicates that most easily degradable carbon has been converted into stable humified organic matter, thereby minimizing nitrogen immobilization after field application, while a pH close to neutrality provides favorable conditions for nutrient availability and beneficial soil microorganisms (Bernal et al., 2009; Manea et al., 2024). Moreover, these characteristics are consistent with the quality criteria specified in the Decree of the Minister of Agriculture of the Republic of Indonesia No. 261 of 2019 concerning the Minimum Technical Requirements for Organic Fertilizers, Biological Fertilizers, and Soil Amendments (Indonesia, 2019), which requires organic fertilizers to meet specified standards for pH, organic carbon, nutrient content, and C/N ratio to ensure product quality, safety, and agronomic effectiveness. Therefore, the physicochemical characteristics achieved by the F5 consortium not only demonstrate successful biodegradation but also indicate that the resulting fertilizer is suitable for practical agricultural application and complies with nationally recognized quality standards.

The practical implications of these findings also extend to agricultural policy and extension services. The use of indigenous bacterial consortia represents a low-cost and locally adaptable biotechnology that can be readily adopted by farmer groups, cooperatives, and agro-industrial enterprises. Extension programs could promote consortium-based co-fermentation technologies as an appropriate method for converting locally available pineapple and palm oil wastes into certified organic fertilizers, thereby reducing production costs while improving environmental sustainability. Furthermore, integrating this technology into regional waste management programs and national organic fertilizer development initiatives would support Indonesia's commitment to sustainable agriculture, waste reduction, and the development of a circular bioeconomy. The adoption of such technologies would simultaneously improve waste management practices, increase resource-use efficiency, and strengthen the resilience of agricultural production systems.

4. Conclusion

This study demonstrated that co-fermentation of pineapple processing waste and palm oil mill waste using indigenous bacterial consortia is an effective strategy for producing high-quality organic fertilizers while simultaneously reducing agro-industrial waste. Increasing the diversity of bacterial isolates consistently improved nutrient enrichment, organic carbon content, compost maturity, and pH stabilization while reducing the C/N ratio. Among the five formulations evaluated, the F5 consortium, comprising fifteen indigenous bacterial isolates, consistently exhibited the best performance under laboratory, pilot-scale, and ex-situ conditions. It produced the highest total $N + P_2O_5 + K_2O$ content and generated mature organic fertilizers with a C/N ratio of 10-12 and pH around 6.0, demonstrating efficient organic matter decomposition, nutrient mineralization, and stabilization. These results highlight the importance of complementary metabolic functions within diverse indigenous microbial communities for enhancing co-fermentation efficiency and fertilizer quality.

The findings demonstrate that the F5 consortium represents a promising biotechnology for sustainable waste valorization by converting pineapple and palm oil processing residues into value-added organic fertilizers. Its consistent performance across different fermentation scales indicates strong potential for practical application and commercial scale-up. From a management perspective, this technology can improve nutrient recovery, reduce agro-industrial waste disposal and dependence on

synthetic fertilizers, and support circular bioeconomy initiatives through resource recycling and sustainable organic fertilizer production. Further research should evaluate the long-term agronomic performance, microbial stability, economic feasibility, and environmental impacts of the F5-derived fertilizers under diverse field conditions to facilitate their wider adoption.

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Data Availability Statement

All the data supporting the results of this study were published in the article itself.

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