

Agro-Industrial Waste Composting Process Enhancement via Microbial Inoculation

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Contributor: Mohd Huzairi Mohd Zainudin

Composting is an important technology used to treat and convert organic waste into value-added products. Recently, several studies have been done to investigate the effects of microbial supplementation on the composting of agro-industrial waste. According to these studies, microbial inoculation is considered to be one of the suitable methods for enhancing the biotransformation of organic materials during the composting process.

Keywords: agro-industrial waste ; composting enhancement ; single-stage inoculation ; multiple-stage inoculation ; bacteria and fungi inoculation

1. Introduction

The increase in human population indirectly contributes to the increasing demand for various agro-industrial-based products. Currently, the agriculture sector contributed 4% (USD 87.7 billion) of the world's Gross Domestic Product (GDP) for the year 2019 ^[1]. The data shown in **Table 1** represents the world's total production and yield of various agro-industrial crops in 2017 and 2018 ^[2]. It can be observed that the production of agro-industrial crops and the yield of the products harvested are increasing year by year to meet the market demand. Hence, the high production of agro-industrial-based products will subsequently increase the generation of waste and residues. Agro-industry is responsible for the production of various residues related to agricultural and industrial activities ^[3]. Looking on the bright side of the waste production trend, these potential substrates can be utilized for recycling which will help to promote the sustainability of the agriculture industry. It is notable that, almost 2.0 billion tons/year of agricultural waste are being produced worldwide with an estimated average increase rate of 5 to 10% per annum ^[4]. Nevertheless, if these residues are discharged into the environment without proper disposal protocol, it may cause great pollution and harmful effects on animal and human health ^[5]. Therefore, effective management of treating these wastes is important to promote the efforts concerning the development of a sustainable society.

Table 1. World's total production and yield based on area harvested for various agro-industrial crops in year 2017 to 2020 ^[2].

		Year			
	Crop	2017	2018	2019	2020
Area harvested (million ha)	Barley	48	48	51.0	51
	Cocoa, beans	12	12	12.0	12
	Coffee, green	10	11	11	11
	Maize	198	195	196	201
	Millet	31	32	30	32
	Oil palm fruit	27	27	28	28
	Oranges	3.8	3.9	3.9	3.8
	Rice, paddy	164	165	161	164
	Sugar beet	4.9	4.8	4.6	4.4
	Sugar cane	26	26	26	26
	Wheat	218	214	215	219

		Year			
	Crop	2017	2018	2019	2020
Production (million tons)	Barley	148	139	158	157
	Cocoa, beans	5.2	5.5	5.6	5.6
	Coffee, green	9.3	10	10	10
	Maize	1138	1124	1141	1162
	Millet	29	32	28	30
	Oil palm fruit	406	409	415	418
	Oranges	73	73	75	75
	Rice, paddy	747	759	749	757
	Sugar beet	313	273	280	252
	Sugar cane	183	193	195	187
	Wheat	772	732	765	761
Yield (hg/ha)	Barley	31,014	29,243	31,060	30,432
	Cocoa, beans	4478	4626	4640	4674
	Coffee, green	9022	9756	9069	9679
	Maize	57,452	57,542	58,127	57,547
	Millet	9212	96,79	9202	9485
	Oil palm fruit	150,255	147,556	146,434	145,614
	Oranges	188,312	192,285	193,660	194,251
	Rice, paddy	45,539	45,795	46,312	46,089
	Sugar beet	630,328	571,355	604,012	569,869
	Sugar cane	697,722	727,979	726,377	706,434
	Wheat	35,377	34,222	35,432	34,744

Among the various waste management systems, composting is considered as the sustainable treatment method for recycling agro-industrial waste into valuable by-products [6]. To date, the production of compost using agro-industrial waste has been extensively used by many researchers due to the availability of cheap and abundant resources [7][8][9]. Agro-industrial waste mainly consists of complex lignocellulosic materials such as cellulose, hemicellulose and lignin. Despite being a suitable method for treating agricultural residues, one of the most common challenges for the composting of this type of waste is the difficulty of decomposing recalcitrant compounds such as cellulose, hemicellulose and lignin. This obstacle affects the productivity of the composting process and the quality of the end product. Moreover, it increases the cost of operations, energy and time in compost production. Various composting strategies had been proposed by researchers aiming to improve the composting process and to produce good quality end-products. This includes monitoring and controlling the key parameters such as C/N ratio, moisture and aeration to provide an optimum condition for composting process. Previous technologies have used pre-treatment methods such as hydrothermal and chemical treatments of the raw materials mainly to break the lignin structure and remove other recalcitrant components before the composting process [10]. However, these pre-treatment methods are not practical, especially for the pilot and industrial scale, due to the high energy and chemical inputs needed. Therefore, finding a safe, sustainable and cost-effective treatment method is necessarily required. Recently, supplementation of microbial inoculant is seen as an attractive solution and there has been growing interest as reported in several studies involving microbial inoculant supplements in the compost pile as a means to enhance productivity and end-product quality of the composting process [11][12][13][14][15].

Various interesting and enlightening studies on the topic of composting of agro-industrial waste, covering the impact of biochar, chemical fertilizer, and mineral amendment have been published and highlighted earlier [16][17]. However, based on the current literature search, limited review articles are describing microbial inoculation, especially for agro-industrial waste composting. The previous study claims that microbial inoculation is less practical than optimizing the

physicochemical parameters of the composting process especially for municipal solid waste [7]. However, recent studies have suggested that inoculation of composting with lignocellulosic waste increase the rate of organic matter degradation, temperature, humification, and maturity [7][18][19]. In view of the effectiveness of microbial inoculation for lignocellulose composting, this review aimed to evaluate the state of the latest developments and the understanding of compost supplementation with microorganisms and their roles in the biotransformation of organic materials during the composting process of agro-industrial waste.

2. Microbial Inoculation with Additional Functions as a Means to Enhance the Composting Process

The impacts of microbial inoculation on the composting of various agro-industrial wastes are summarized in **Table 2**. Previous studies reported that inoculation of microbes into the composting led to improved mineralization [20], accelerated the composting process of OPEFB from 64 days to 50 days [21] and enhanced the compost maturity of rice straw and cattle manure by an increase in total nitrogen, phosphorus and potassium content [22]. The re-inoculation of microbial agents *Aeromonas caviae* sp. SD3 *Shinella* sp. XM2, *Rhizobium* sp. S8 *Corynebacterium pseudotuberculosis* sp. SD1 and *Streptomyces clavuligerus* sp. XM which were screened from rice straw compost into the composting pile accelerated the degradation of organic matter and coarse fiber content by 7.58% and 8.82%, respectively due to the enhancement of key enzymes (CMCase, xylanase) and core microbial metabolisms [23]. Moreover, inoculation of a microbial inoculum consisting of *Ralstonia* sp. (LT703298), *Penicillium* sp. (LT703297), *Penicillium aurantiogriseum* (LT703295) and *Acremonium alternatum* (LT703296), with abilities for cellulose and lignin degradations improved the enzymatic activities of cellulase (15.0 to 19.8%), urease (2.3 to 71.4%), polyphenol oxidase activities (0.3 to 28.4%) and thus, shorten the composting period and improved the maturation rate as compared to the control treatment (uninoculated) in pig manure and apple tree branch composting [24]. Henry et al. [25] reported the addition of effective microbes (EM) in the composting of chicken manure, rice bran and pine waste could enhance the population of thermophiles which consequently improved the composting rate as compared to the control composting. The finding by Wang et al. [9], showed that the inoculation of a bacterial consortia inoculant reduced the C/N, organic matter and moisture, and promotes the enrichment of *Bacillus*, *Sphingobacterium* and *Saccharomonospora* genus, which enhanced the pectin and cellulose degradation during the composting of citrus peel, bran and lime. Furthermore, inoculation of phosphate-solubilizing bacteria into the composting of sugarcane waste enhanced bacterial growth, mainly of the order *Lactobacillales*, triggering the rise of temperature at the initial phase which promoted the degradation of the lignocellulosic content and consequently enriched phosphorus content at the end of the composting [26].

Table 2. Summary of the impact of microbial inoculation on the agro-industrial waste composting by several works of literature.

Compost Materials	Inoculum/ Microorganisms	Rate of Inoculum Addition	Composting Conditions	Impact on the Entire Composting Process	References
Mushroom residue	<i>Paenibacillus</i> GX 5 <i>Paenibacillus</i> GX 7 <i>Paenibacillus</i> GX 13 <i>Brevibacillus</i> GX 5 <i>Brevibacillus</i> GX 7 <i>Brevibacillus</i> GX 13	2 mL 100 g ⁻¹	C/N ratio (12), Temperature (57 °C), MC (60 to 24%), pH (8)	Improved degradation rate of lignocellulose and organic matter, prolonged thermophilic period, enhanced microbial interaction.	[19]
Mushroom residue and wood chips	<i>Aspergillus</i> , <i>Penicillium</i> , <i>Bacillus</i> , <i>Streptomyces</i>	0.2% (w w ⁻¹)	C/N ratio (22), Temperature (58.4 °C), MC (50%), pH (7.8)	Prolonged thermophilic stage, increased degradation efficiency of cellulose and hemicellulose, optimizing the microbial community structure.	[18]
Chicken manure and maize straw	Strains isolated from natural chicken manure and maize straw compost: <i>Bacillus licheniformis</i> , <i>Bacillus amyloliquefaciens</i> , <i>Ureibacillus thermosphaericus</i> , <i>Bacillus megaterium</i> , <i>Geobacillus pallidus</i> , <i>Bacillus pumilus</i> , <i>Geobacillus</i> sp. <i>Paracoccus denitrificans</i>	200 mL with 1 × 10 ⁸ CFU mL ⁻¹ cell concentration	C/N ratio (21), Temperature (68.4 °C), MC (55.6 to 42%), pH (8.7)	Increased germination index, NO ₃ content, prolonged thermophilic stage, reduced volatile solids contents, improved humification and compost maturity level.	[15]

Compost Materials	Inoculum/ Microorganisms	Rate of Inoculum Addition	Composting Conditions	Impact on the Entire Composting Process	References
Chicken manure and rice husk	<i>Ureibacillus terrenus</i> BE8 and <i>Bacillus tequilensis</i> BG7	5% (v w ⁻¹)	Total C (263 g kg ⁻¹), and Total N (34 g kg ⁻¹), Temperature (65 °C), MC (78.1%)	Enhanced germination index values, accelerated compost maturity by stimulating different key microbes at the initial stage which promotes better phytotoxicity-free compost than the control treatment.	[27]
Pig manure and wheat straw	Microbial agent solution consisting of photosynthetic bacteria, actinomycetes, yeasts, and lactic acid bacteria	40 mL 10 kg ⁻¹	Total C (41.2 ± 0.5%), Total N (1.79 ± 0.03%), Temperature (68.4 °C), MC (55%)	Changes in ARG profiles and bacterial communities have promoted the changes in the potential hosts of ARGs, thus increasing the removal of total ARGs.	[28]
Rice straw	Compound bacterial agent screened from rice straw composts: <i>Aeromonas caviae</i> sp. SD3 (KR868995.1), <i>Shinella</i> sp. XM2 (CP015736.1), <i>Rhizobium</i> sp. S8 (KF261556.1), <i>Corynebacterium pseudotuberculosis</i> sp. SD1 (CP020356.1) and <i>Streptomyces clavuligerus</i> sp. XM (CP032052.1)	1% (w w ⁻¹) with 1 × 10 ⁹ CFU mL ⁻¹ cell concentration	C/N (30), MC (65%)	Improved the degradation of organic matter and coarse fiber content by 7.58% and, 8.82% due to the enhancement of core microbial metabolism.	[23]
Chicken manure, rice bran and pine waste	Bacteria: <i>Bacillus</i> spp., <i>Alicyclobacillus</i> spp., <i>Pseudomonas</i> spp., <i>Lactobacillus</i> spp., <i>Pediococcus</i> spp., and <i>Actinomycetes</i> . Fungi: <i>Rhizomucor pusillus</i> , <i>Aspergillus</i> spp.	0.2% (w w ⁻¹)	C/N ratio (28.4), Temperature (65 °C), MC (60 to 40%), pH (8.5)	Increased microbial diversity and population, enhanced in composting rate and mineralization.	[25]
Rice straw biogas residue and rice straw	<i>Aspergillus niger</i> CICIMF0410 and <i>P. chrysosporium</i> AF 96007	1% (v w ⁻¹) with 1 × 10 ⁸ CFU mL ⁻¹ cell concentration	C/N ratio (32), Temperature (68.3 °C), MC (60%)	Reduced the time required for decomposition of organic matter, removed the toxicity risk for crops and promoted the stability of the compost.	[29]
Swine manure and spent mushroom substrate	Microbial suspension of lignocellulose-degrading microorganism's consortium consisting of <i>Bacillus</i> , <i>Brevibacillus</i> , <i>Paenibacillus</i> and <i>Lysinibacillus</i> genera	10% (v w ⁻¹)	Mixture ratio (1:1), Temperature (68 °C), MC (60%), pH (7.6)	Promoted the changes of the bacterial community in the mesophilic phase and reduced the risk of ARGs in the final compost.	[30]
Maize straw and canola residue	<i>Phanerochaete chrysosporium</i>	1 × 10 ⁸ CFU mL ⁻¹	C/N ratio (25), Temperature (60 °C), MC (52%), pH (8.17)	Improved lignin degradation during the cooling stage, enhanced compost humification.	[13]
River sediment, rice straw, vegetables, and bran	<i>Phanerochaete chrysosporium</i>	0.5% (v w ⁻¹)	C/N ratio (30), Temperature (69 °C), MC (60%), pH (8.6)	Enhanced the passivation of copper and reduced the effect of pH on the bioavailability of heavy metals.	[31]

Compost Materials	Inoculum/ Microorganisms	Rate of Inoculum Addition	Composting Conditions	Impact on the Entire Composting Process	References
Dairy manure and sugarcane leaves	Thermophilic lignocellulolytic microbes screened from dairy and sugarcane leaves compost samples: <i>Bacillus licheniformis</i> (TA65), <i>Aspergillus nidulans</i> (GXU-1) and <i>Aspergillus oryzae</i> (GXU-11)	2% (w w ⁻¹)	C/N ratio (30), Temperature (55 °C),	Improve the mineralization of organic carbon, promoted the lignocellulose degradation and the humification process.	[32]
Pig manure and corn stalk	Compound bacterium agent comprised of <i>Acinetobacter pittii</i> , <i>Bacillus subtilis</i> sub sp. <i>Stercoris</i> and <i>Bacillus altitudinis</i>	1% (v w ⁻¹) with 1 × 10 ⁹ CFU mL ⁻¹ cell concentration	C/N ratio (30), Temperature (67.3 °C), MC (60%), pH (8.8)	Prolonged at the thermophilic stage, decreased abundance of human disease-related functional genes, increased the numbers of biomarkers and enhanced the maturity and fertility.	[33]
Citrus peel, bran and lime	The bacterial consortium which was screened from citrus peel compost samples	3% (w w ⁻¹)	C/N ratio (25), Temperature (65 °C), MC (60%), pH (8.5)	Decreased C/N, organic matter, moisture, pectin and cellulose content, and enhanced the richness and diversity of the bacterial community.	[9]
Cattle manure and wheat stalks	<i>Bacillus subtilis</i>	0.5% (w w ⁻¹)	C/N ratio (25), MC (60%), pH (7.61)	Promoted changes in ARGs and removed a large number of pathogenic bacteria.	[34]
Wheat straw, rice, corn and soybean	Actinomycetes: <i>Streptomyces</i> sp. H1 (KX641927.1), <i>Mycobacterium</i> sp. G1 (KY910181.1), <i>Micromonospora</i> sp. G7 (LC333394.1) and <i>Saccharomonospora</i> sp. T9 (NR074713.2)	3 mL kg ⁻¹ with 1 × 10 ⁹ CFU mL ⁻¹ cell concentration	C/N ratio (30), Temperature (63 °C), MC (50 to 60%), pH (9.4) and the aeration rates: 0.5 L kg ⁻¹ (dry matter) min ⁻¹	Improved 34.3% lignocellulose degradation and 8.3% enzyme activity.	[35]
Pig manure and apple tree branches	Microbial inoculum: <i>Ralstonia</i> sp., <i>Penicillium</i> sp., <i>Penicillium aurantiogriseum</i> , and <i>Acremonium alternatum</i>	2% (v w ⁻¹)	C/N ratio (30), Temperature (77 °C), MC (60%), pH (8.1)	Enhanced cellulase, urease, and polyphenol oxidase activities and promoted the succession of the bacterial community structure.	[24]
Corn straw and dairy manure	Thermotolerant actinomycetes <i>Streptomyces</i> sp. H1, <i>Streptomyces</i> sp. G1, <i>Streptomyces</i> sp. G2 and <i>Actinobacteria</i> bacterium T9	2% (v w ⁻¹) with 1 × 10 ⁹ CFU mL ⁻¹ cell concentration	C/N ratio (30), Temperature (57 °C), MC (60%)	Enhanced cellulase activities and increased degradation of cellulose, humic substances content.	[36]
Food waste and maize straw	Cold adapted microbial consortium comprised of strains <i>Pseudomonas fragi</i> (KY283110), <i>Pseudomonas simiae</i> (KY283111), <i>Clostridium vincentii</i> (KY283112), <i>Pseudomonas jessenii</i> (KY283113) and <i>Iodobacter fluvialis</i> (KY283114).	1% (v w ⁻¹) with 1 × 10 ⁸ CFU mL ⁻¹ cell concentration	C/N ratio (18), Temperature (45 °C), MC (66%)	Increased organic matter degradation at low temperature and promoted the change of the bacterial community composition and succession.	[37]

Compost Materials	Inoculum/ Microorganisms	Rate of Inoculum Addition	Composting Conditions	Impact on the Entire Composting Process	References
Dairy manure and rice straw	Psychrotrophic-thermophilic complex microbial agent (PTCMA): <i>Bacillus diminuta</i> CB1, <i>Flavobacterium glaciei</i> CB23, <i>Aspergillus niger</i> CF5 and <i>Penicillium commune</i> CF8	10 mL kg ⁻¹ with 1 × 10 ⁸ CFU mL ⁻¹ cell concentration	C/N ratio (32), Temperature (63 to 45 °C), MC (60%), pH (8.2 to 8.4)	Increasing the composting pile temperature and significantly enriched compost Maturity and proposed inoculation of PTCMA is an effective approach in cold climates.	[38]
Sugarcane industry waste	Phosphate-solubilizing bacteria: <i>Pseudomonas aeruginosa</i> , <i>Bacillus</i> sp., <i>Lactobacillales</i> , <i>Bacillales</i> , <i>Pseudomonas</i> sp., <i>Clostridiales</i>	8 L mg ⁻¹ with 1 × 10 ⁸ CFU mL ⁻¹ cell concentration	C/N ratio (30), Temperature (60 °C)	Enhanced bacterial growth, mainly of the order <i>Lactobacillales</i> , thus causing the heating of the piles during the initial phase and enriched phosphorus content at the end of composting.	[26]
Rice straw, soil, vegetables, and bran	<i>Phanerochaete chrysosporium</i>	2% (v w ⁻¹) with 1 × 10 ⁶ CFU mL ⁻¹ cell concentration	C/N ratio (30), Temperature (58 °C), MC (60%), pH (8)	Decreased the toxicity of lead and increased the diversity of bacterial community in the composting.	[39]
Chicken manure and rice straw	Ammonia-oxidizing bacteria	5% (v w ⁻¹) with 1 × 10 ⁶ CFU mL ⁻¹ cell concentration	C/N ratio (25), Temperature (57 °C), MC (60 to 70%), pH (7.4) aeration rate: 0.5 L/min	Decreased ammonia emission and nitrogen loss by transforming ammonium into nitrite and also enhanced the abundance of bacterial community.	[40]
Rice straw	Cellulase producing bacteria: <i>Bacillus licheniformis</i> 1-1v and <i>Bacillus sonorensis</i> 7-1v	1% (v w ⁻¹) with 3.6 and 6.8 × 10 ⁷ CFU mL ⁻¹ cell concentration	C/N ratio (35.8), Temperature (54 °C), MC (35%), pH (8.1)	Shortened the composting time by 40 to 43%, resulting in a higher decrease in the total organic carbon and C/N ratio and enriched compost quality.	[22]
Vegetable waste: cattle manure: sawdust	<i>Phanerochaete chrysosporium</i> (MTCC 787)	10 ⁷ to 10 ⁸ spores g ⁻¹ of compost	Compost mixture ratio (5:4), Temperature (64 °C), MC (65%), pH (7.5)	Enhanced the volatile solids reduction by 1.45-fold in trial 2 (initial phase) and 1.7-fold (thermophilic phase) in trial 3 as compared to uninoculated compost treatment.	[41]
Rice straw and goat manure	EM: lactic acid bacteria, yeast and phototrophic bacteria.	5% (v w ⁻¹)	C/N ratio (32.4)	Improved the mineralization in composting process.	[20]
Wheat straw and cattle manure	Ammonium-oxidizing bacteria: Bacillaceae (strain T-AOB-2, M-AOB-4 and MT-AOB, 2-4)	5% (v w ⁻¹) with 1 × 10 ⁸ CFU mL ⁻¹ cell concentration	C/N ratio (30), MC (65%)	Promote formation of humic substances by reducing total organic carbon and dissolved organic carbon, improving bacterial activity.	[42]
Chicken manure, fufural residues and bagasse	Exogenous microbes (VT) and indigenous microbes (M3T)	0.5% (v w ⁻¹)	C/N ratio (30), Temperature (50 to 58 °C), MC (55%)	Improved rate of temperature increase, enhanced urease, protease and cellulase activity.	[43]

Compost Materials	Inoculum/ Microorganisms	Rate of Inoculum Addition	Composting Conditions	Impact on the Entire Composting Process	References
Maize straw and pig manure	<i>Bacillus subtilis</i> , <i>Bacillus licheniformis</i> , <i>Phanerochaete chrysosporium</i> , <i>Trichoderma koningii</i> , <i>Saccharomyces cerevisiae</i>	0.1% (w w ⁻¹)	C/N ratio (27.7), Temperature (66 °C), MC (60%)	Improved rate of temperature increase, increased micronutrients (N, P, K), enhanced decomposition of organic carbon, improved germination index.	[44]
Wheat straw and dairy manure	Microbial agent: <i>Aspergillus niger</i> , <i>Saccharomyces cerevisiae</i> , <i>Lactobacillus plantarum</i> , <i>Lactobacillus acidophilus</i> , <i>Bacillus megaterium</i> , <i>Streptomyces albogriseus</i> and <i>Bacillus subtilis</i>	0.2% (v w ⁻¹)	C/N ratio (16), Temperature (60 °C), MC (60%), pH (8.0)	Increased composting maturity and total organic carbon degradation, decreased abundance of potential pathogen and improved key bacterial network interaction.	[45]
Rice straw and cattle manure	<i>Malbranchea cinnamomea</i> , <i>Gloeophyllum trabeum</i>	10 mL kg ⁻¹	C/N ratio (25), Temperature (73 °C), MC (65%), pH (8.5)	Promoted cellulose, hemicellulose and lignin degradation, increased nutrients and humus carbon, increased diversity and relative abundance of lignocellulosic fungi.	[46]
Rice straw and swine manure	<i>Kitasatospora phosalacinea</i> C1, <i>Paenibacillus glycanilyticus</i> X1, <i>Bacillus licheniformis</i> S3, <i>Brevibacillus agri</i> E4 and <i>Phanerochaete chrysosporium</i>	Not mentioned	C/N ratio (27.5), Temperature (62 °C)	Improved rate of temperature increase, enhanced maturation level.	[47]
Wheat straw and swine manure	<i>Gloeophyllum trabeum</i>	1 × 10 ⁸ spores kg ⁻¹	C/N ratio (27), Temperature (73 °C), MC (60%)	Shorten maturation period, increased decomposition rate of cellulose, hemicellulose and lignin, influencing fungal community by increasing relative abundance of <i>Aspergillus</i> , <i>Mycotremus</i> and <i>melanocapus</i> .	[48]

Another finding by Wan et al. [15] revealed that the addition of a microbial cocktail inoculum consisting of *Bacillus licheniformis*, *Bacillus amyloliquefaciens*, *Bacillus megaterium*, *Bacillus pumilus*, *Geobacillus pallidus*, *Ureibacillus thermosphaericus* and *Paracoccus denitrificans* which were isolated and cultivated from chicken manure and maize straw compost itself enhanced the thermophilic phase of composting process with maximum temperature reaching 68 °C as compared to the control treatment with only 60.8 °C as the maximum temperature. Due to this, the germination index increases as high temperature reduced the phytotoxicity effect and thus contributed to the better maturity level of the compost [49]. Previously, Zhang et al. [40] reported the inoculation of enriched ammonia-oxidizing bacteria successfully reduced ammonia emission by 53% of total ammonia than uninoculated compost by promoting ammonia transformation into nitrate. The inoculation of combined bacterial agents (*Acinetobacter pittii*, *Bacillus subtilis* sub sp. *Stercoris* and *Bacillus altitudinis*) influenced the bacterial community succession and prolonged the thermophilic stage of the composting of pig manure and corn stalk by 2 days [33]. The inoculation of these microbes also increased the total phosphorus and showed no plant toxicity at the end of the composting process. Their findings showed that the extended thermophilic period reduced the abundance of human disease-related functional genes which was due to the elimination of a large number of pathogenic bacteria.

Liu et al. [27] reported that the germination index of the chicken manure and rice husk composting reached 80% within 13 days with the addition of microbial inoculants as compared to control which took 21 days to reach this value. The higher GI achieved was attributed to the increase in fluorescence intensity of fulvic acid-like and humic acid-like substances detected, indicating inoculation of microbes promotes the biotransformation of water-extractable organic matter and also the compost maturity. Zhang et al. [50] suggested that compost with more than 80% GI could be considered as matured

and phytotoxicity-free. Similarly, inoculation of *Phanerochaete chrysosporium* at the cooling phase of the composting of maize straw and canola residues showed the higher GI (103.11%) as compared to the control (without inoculation) and inoculation at the initial phase with GI at only 90.65% and 96%, respectively [13].

To date, fungal inoculation had shown its effectiveness for enhancing the composting process. One of the significant and widely used fungi in composting is white-rot fungus *Phanerochaete chrysosporium* that produces the extracellular enzymes system consisting of manganese peroxidase, lignin peroxidase and laccases for lignocellulose degradation [41]. Huang et al. [39] demonstrated that inoculation with *Phanerochaete chrysosporium* significantly reduced the toxicity in the composting of lead (Pb)-contaminated rice straw, soil, vegetables and bran. Likewise, via DGGE profile analysis, *Phanerochaete chrysosporium* showed a positive impact on the bacterial community composition which contributed to the reduction of toxic Pb^{2+} ions concentration. A study by Chen et al. [31] also showed that the inoculation of *Phanerochaete chrysosporium* reduced the bioavailability of heavy metals for cadmium, plumbum and zinc, respectively, as compared to non-inoculated composting of agricultural waste and river sediment. This is due to the fact that *Phanerochaete chrysosporium* promotes the passivation of heavy metals through chelation action by organic humus. It was also found that the inoculation with *Phanerochaete chrysosporium* showed greater passivation of copper than other heavy metals during the composting process.

Furthermore, the inoculation of *Phanerochaete chrysosporium* at the initial and thermophilic stages in the co-composting of vegetable waste, cattle manure and sawdust at ratio 5:4:1 promoted the volatile solids reduction by 1.45-fold (initial phase) and 1.7-fold (thermophilic phase) as compared to the uninoculated compost treatment [41]. Wan et al. [15] reported the inoculation of microbial cocktails in the composting pile also improved the reduction of volatile solids from initial content of 44% in both piles to final content of 29.9% for the inoculation and 32.1% for the control treatment. The reduction of the volatile solids was mainly due to the volatilization of ammonia gases during the composting process [51]. Additionally, the combination of *Aspergillus niger* and *Phanerochaete chrysosporium* reduced the composting time by improving the degradation rates of hemicellulose, cellulose and lignin by 29.4%, 34.8% and 40.5%, respectively, as compared to the control treatment [29]. Moreover, the inoculation of both fungi promoted the maturity level of compost through the enhancement of humification with higher humic acid content (10.5% to 18.6%) and humification index (1.69 to 2.64) in 30 days of the composting process. Another finding by Xu et al. [32] revealed the degradation rate of cellulose and hemicellulose for inoculated dairy manure-sugarcane leaves composting (27%) was higher than that of the uninoculated composting (22%). Inoculation also promoted the formation of humic substance compost by 11.82% higher than that of the uninoculated one. Hence, Xu et al. [52] concluded that the inoculation of efficient microbes could enhance the metabolism of easily available organic compounds and the organic matter of the composting process. In addition, Wei et al. [35] revealed that the inoculation of actinomycetes in the composting of wheat, rice, corn and soybean straw improved by 34.3% lignocellulose degradation and by 8.3% enzyme activity. These results were in agreement with the studies reported by Zeng et al. [53] which demonstrated that with the inoculation of *Phanerochaete chrysosporium* during the mesophilic cooling phase of the composting of agricultural wastes (mixture of rice straw, vegetables, rice bran and soil) enhanced the xylanase, manganese peroxidase and lignin peroxidase activity which then increased by 40% lignocellulose degradation ratio. Similarly, thermotolerant cellulolytic actinomycetes (*Streptomyces* sp. H1, *Streptomyces* sp. G1, *Streptomyces* sp. G2 and Actinobacteria bacterium) which were inoculated into different (initial, thermophilic and cooling) stages of composting were reported to enrich cellulase activities, enhance the degradation of cellulose, increase the content of the humic substances and subsequently influence the structure of the actinomycete community in dairy manure-corn straw composting [36].

In general, composting is conducted in an environment with ambient temperatures between 20 °C to 30 °C. However, in cold climates conditions such as winter with temperatures usually lower than 15 °C, it is difficult to operate the composting process due to the slow metabolism of microbes that contributes to the suppression of microbial heat generation in the piles [54]. As a solution, the inoculation of cold-adapted and thermophilic microbial agents consisting of *Brevundimonas diminuta* CB1, *Flavobacterium glaciei* CB23, *Aspergillus versicolor* CF5 and *Penicillium commune* CF8 successfully increased the temperature at the onset of composting and significantly improved the compost maturity by decreasing the total organic carbon and C/N ratios, as well as promoting the increment of total nitrogen, degradation of cellulose and lignin, and germination index than the control compost [38]. This was in agreement with Xie et al. [37] who showed that the inoculation of a cold-adapted microbial consortium consisting of strains *Pseudomonas fragi* (KY283110), *Pseudomonas simiae* (KY283111), *Clostridium vincentii* (KY283112), *Pseudomonas jessenii* (KY283113) and *Iodobacter fluvialis* (KY283114) significantly enhanced the degradation of organic matter and increased the temperature when the food waste was composted at low ambient temperature (10 °C), contributing to start-up composting in winter or cold regions.

It is also important to highlight that, composting is regarded as an effective method to eliminate antibiotic resistance genes (ARGs) present in the waste especially manure. Manure application has been shown to increase the occurrence and

spread of ARG in soils that may enter the food chain via contaminated crops and groundwater, hence, posing a potential risk to human health [55]. As reported by Cao et al. [28] the addition of microbial agents composed of photosynthetic bacteria, actinomycetes, yeasts and lactic acid bacteria in the composting increased the reduction of total ARGs by changing the variations of ARG profiles and the potential hosts of ARGs (bacterial community) which subsequently influences the removal of ARGs. Similarly, the inoculation of 0.5% (w/w) of *Bacillus subtilis* into the composting of cattle manure and wheat stalks mixture decreased the relative abundances of ARGs, mobile genetic elements and human pathogenic bacteria (by 2 to 3 logs) in the composts [34]. Furthermore, it was reported that the inoculation of microbial suspension of lignocellulose-degrading microorganisms consisting of mainly *Bacillus*, *Brevibacillus*, *Paenibacillus* and *Lysinibacillus* genera, decreased the total relative abundance of ARGs by 0.08 logs and affected the bacterial community structure in the mesophilic phase, with the inhibitory effect of potential pathogens during the composting of swine manure and spent mushroom substrate as compared to control treatment [30]. Hence, the addition of inoculum could potentially reduce the ARGs, inhibit pathogens, as well as making the final compost products safer.

Although microbial inoculation has demonstrated some outstanding effects on the composting process, the economic feasibility of this technology should be considered so that it could be applied at the pilot or large-scale production levels. Many of the success stories of this technology are mainly based on small-scale production. As far as we know, there is only a study done by Yoshizaki et al. [56], who evaluated the economic viability of composting of an agro-industrial waste, oil palm biomass which is oil palm empty fruit bunch (OPEFB), with sludge containing microbial seeds at the semi-industrial and commercial-scale production in Malaysia. In this study, the palm oil mill effluent (POME) anaerobic sludge from the anaerobic digester and OPEFB were used as the composting material. Their findings showed that the composting of 11,570 tons of EFB and POME anaerobic sludge produced 579 tons of nitrogen, 151 tons of phosphorus and 761 tons of potassium per year. It was estimated that the produced compost could provide a 32% internal rate of return (IRR) of USD 9.53 million of net present value (NPV) and 2.9 years for the payback period (PBP) of the investment in 10 years. However, the economic analysis of composting with raw POME showed that the IRR, NPV and PBP for 10 years were 8%, USD 0.43 million and 6.5 years, respectively, which is 24% and USD 9.1 million less and 3.6 years longer than that of composting with POME anaerobic sludge. The results indicated that composting with POME anaerobic sludge was more effective as compared to composting with raw POME. The reason might be that the raw POME did not provide enough microbial seeding and nutrient resources, owing to its diverse characteristics. Unlike raw POME, POME anaerobic sludge generated from the anaerobic digester demonstrated higher nutritional and microbial seed contents with consistent characteristics. Therefore, the higher IRR and faster PBP could be due to the enhancement of the composting process through the application of palm oil mill effluent anaerobic sludge consisting of not only nutrients but also various beneficial indigenous microorganisms which reduced the degradation time, from 60 days to 40 days, with acceptable quality and maturity of the composting product [57][58]. The microbial seed present in the POME anaerobic sludge made this material highly applicable and economically viable as no additional microbes and enzymes were required in order to maintain the quality of the product. It is important to note that the supplementation of single or multiple microbes and enzymes would contribute to the additional annual cost of operations and maintenance. Therefore, developing the optimal methods of microbial seeding is required to ensure that this technology is economically viable especially in pilot or industrial-scale production. In addition, several bacterial strains including *Citrobacter sidlakii* and *Bacillus tequilensis* with multiple functions such as plant growth promotion, biocontrol and lignocellulose degradation were successfully isolated from the OPFEB-POME anaerobic sludge compost [59]. Therefore, the produced OPFEB-POME anaerobic sludge compost can be a prodigious replacement for mineral fertilizer as it contains not only high nutrient content, but also a beneficial microbe that is good for soil amendments and crop growth. As a result, the cost for feedstock of the composting process and chemical/inorganic fertilizer could be cut down significantly with the application of composts. Yoshizaki et al. [56] also pointed out that the OPEFB-POME anaerobic sludge compost can replace around 3,250 tons of the conventional chemical fertilizer used to fertilize the palm tree in the plantation.

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