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REVIEW

Agrowaste bioconversion and microbial fortification have prospects for soil health, crop productivity, and eco-enterprising

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Abstract

Purpose Agricultural chemicals either used as nutrient inputs for soil fertility or pesticides are creating physicochemical and biological deterioration of the soils and disturbing the agro-ecosystems worldwide. Alarming concerns towards integrated agroecology demand for renewed interest in low-external input-based farming practices. These practices comprise strengthening of soil biological properties, recycling of inherent soil minerals and reuse of agricultural residual wastes.

Methods We described approaches for the bioconversion of agricultural residual wastes into value-added compost. The process involves conversion of residual waste into raw compost followed by its fortification with beneficial decomposer microorganisms to produce quality fortified compost product. Finally, incubation of fortified compost with single or consortia of beneficial microorganisms like N-fixers, P-solubilizers or K-mobilizers and biocontrol agents further enriches compost to produce bioorganic products.

Results Bioconversion of agricultural wastes into compost using potential decomposer microorganisms and fortification of decomposed organic matter with beneficial bacterial and fungal species is of immense importance. Additional enrichment of compost with botanicals, humic acid, amino acids, mineral nutrients, phytohormones etc. may also add value to the bioinput products.

Conclusion In an integrated way, on-farm production of raw compost using different agricultural residual wastes and its further fortification with bioorganic farm inputs can help farmers produce value-added compost products for direct application in the crop production. Adoption of microbial bioconversion technologies and their field applications may become eco-enterprising for the rural resource-poor farming communities for enhancing their livelihood along with improving farm productivity and soil health.

Keywords Microbial technology · Agricultural wastes · Bioconversion · Compost · Microbial inoculants · Bioorganic farm inputs

Introduction

Agricultural production has always been increasing pace due to the use of high-yield varieties which were input-intensive and demanded excessive chemical fertilizers and pesticides for supporting soil fertility and plant nutrition (Kibblewhite et al. 2008; Lorenz et al. 2013). Indiscriminate use of chemical inputs into the agricultural system has raised several problems concerned with the groundwater quality, soil agroecology and plant health (Power 2010). This has led to serious deleterious polluting impact on soil fertility, crop production, irrigation water, nutritional produce quality, and human health (Popp et al. 2013). Soils are continuously becoming low in organic carbon content and losing beneficial microbial communities. Agricultural chemicals have altered traditional cultivation practices and created physical, chemical, and biological deterioration of cultivable lands (Pretty and Bharucha 2014). Excessive chemical use has adversely influenced biodiversity of the soils, caused loss of nutritional ingredients and accumulation of non-desirable chemical intermediates in the food chain (Lal 2015). Other major problem associated with the chemical-dependent agricultural system is the increasing contamination of surface and groundwater due to residual pesticides, industrial

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wastes, heavy metals, and organic chemicals (Jaishankar et al. 2014; Khatri and Tyagi 2015).

Health of agricultural production system is at stake in the wake of shrinking land resources, increasing industrialization, expanding urbanization, excessive chemical usage and diminishing viable bioorganic inputs in the soils (Phalan et al. 2014). Agricultural sustainability is compromised due to the reducing biological wealth of farm resources. This needs to be suitably addressed to sustain long-term agricultural productivity to support food security and rural livelihood (Frison et al. 2011; Pradhan et al. 2015). There exists no simple or single way to understand and implicate such complex ecological, socioeconomic, and technological aspects of declining sustainability in agricultural systems (Pretty and Bharucha 2014). However, addressing connection between a balanced agro-ecosystem and sustainable crop productivity in a holistic manner could offer better solution to restore sustainability in agriculture systems.

Public concerns over adverse impacts of external chemical inputs on the quality of produce, farm soils, water and environment are rising (Bohlke 2002; Aktar et al. 2009; Mohanty et al. 2013; Hongsibsong et al. 2017). This has raised questions as to whether the present agricultural production system is able to provide quality food for all-over longer term (Hossard et al. 2014; Pradhan et al. 2015). Therefore, many countries are now taking initiatives to reduce the use of fertilizers and pesticides in the food crop production system (FAO 2017). Green Revolution witnessed high pace of crop productivity in the past few decades. However, now this has left with emerging associated risks of dependence on high external inputs, disturbance of agroecology and resurgence of pests and diseases (Pingali 2014; Godfray and Garnett 2014). Such threatening concerns have generated renewed interest in the alternative ways of farming practices that are based on recycling and reuse of farm wastes as bioorganic inputs to enhance soil productivity (Schröder et al. 2018). This has also provoked current thinking on intensified promotion of soil biodiversity and biogeochemical processes that enhance soil carbon and microbial communities having specific functional traits (Gattinger et al. 2012; Lori et al. 2017). Results from long-term experimental data generated on nitrogen fertilization strategies in Italy for limiting environmental risk from excessive N-application and animal farming created Nitrates Directives application scheme for more relaxed application of manure-N. Studies reflected that application of composted materials with bacterial biofertilizers improved soil microbial community structure and diversity in degraded soils from croplands (Zhen et al. 2014). Similar practices can balance bioorganic and microbiological equilibrium of the soils in the ways that simultaneously favor production and protection of food crops along with the soil fertility status.

Crop production strategies based on low external input farming practices that nurtured ecological dynamics have potentials of minimizing chemical fertilizers, inorganic inputs and pesticides. This has reliably led to reducing the cost of production, producing high-quality nutritionally valuable and sellable crop produce, ensuring ecological safety and rural livelihood and most importantly, holistic human health (Kesavan and Swaminathan 2008). In such a farming system, crop yield is maintained through greater emphasis on cultural practices, use of biological inputs, integration of pest/disease management practices and managed utilization of on-farm agricultural resources (Gliessman and Rosemeyer 2010; Branca et al. 2011; Osteen et al. 2012). Making the soils rich in organic carbon support diverse microbial inhabitants that in turn promote soil functions (Gougoulias et al. 2014; Trivedi et al. 2016). Global land distribution and soil quality are compromised due to high pressure to produce more crops, changing pattern in global food consumption, insufficient adoption of soil management practices, urbanization, and industrialization and life style of the population (Blum 2013). The role of organic carbon richness in the soils in terms of its functional benefits is obvious (Clara et al. 2017). Usually low-carbon soils fail to support diverse microbial attributes that naturally drive ecosystem functions independently (Louis et al. 2016). Therefore, there is a need to implicate enhanced availability of organic matter in the soils for sustainable improvement in crop productivity and tolerance against biotic and abiotic stresses (Zhang et al. 2016). Site-specific organic carbon content in the top-soils is a major prerequisite for sustainable soil functions indicating a good soil quality and agronomic value (Seremesic et al. 2011). Decline in soil organic matter due to insufficient addition of organic manures, low crop rotation and management practices (like tillage, fertilization) and on-farm crop residue burning is widely reported (Bhan and Behera 2014; Godde et al. 2016). The organic content of the soils can be improved by increasing organic matter gain of the soils through the addition of decomposed materials or by reducing organic matter losses through released respiring carbon by microorganisms (Carter 2002).

One of the potential sources of organic carbon return to the soils is the crop residue produced during the cropping season and post harvest. These residues usually go waste and create environmental sanitation issues. However, if incorporated in the soils it can increase crop yield (Han et al. 2017). Loss of organic carbon from the soil reduces crop productivity worldwide. Therefore, locally feasible practices are needed to support farmers to help regain soil organic matter (Wei et al. 2015). Farmers usually lack knowledge on the importance of microbial resources in the above-ground and below-ground soils and benefits of their on-farm implications. They also lack information on biological management of farms using microbial technologies, potentialities of managed integration of on-farm resources and conversion of agro-wastes into organic farm inputs to enhance soil capabilities (Han et al. 2017). These issues, if accepted, worked out and adapted by the resource-poor farmers can help in minimizing dependency on external chemicals and fertilizers, reducing cost of crop production and improving ecosystem services in the soils. Therefore, the agricultural residue decomposition technology using microbial interventions and fortification of the compost with beneficial microorganisms has immense scope.

We reviewed significance of microbe-mediated agrowaste bioconversion practices and their reuse for strengthening soils. We described how fortification and bioaugmentation of the raw decomposed products using specific microbial inoculants that act as decomposers, plant growth promoters and/or bioagents can help farmers obtain functionally potential bioorganic farm inputs? The usefulness of such technologies in producing different crops has also been summarized with specific examples from the field-scale applications.

Microorganisms are the key to agrowaste bioconversion

The ways in which microorganisms have been used to advance human and animal health, food processing, food safety and quality, environmental protection, crop production, and agricultural biotechnology has made them alternatives for high-input farming practices. Lignocellulose that consists of cellulose, hemicellulose and lignin represents major structural component of agricultural crop residues (Pothiraj et al. 2006). Due to extensive agricultural activities, huge amounts of agricultural residues contribute significantly to the yearly global yield of lignocellulose (Loow et al. 2015). Various agricultural residues that contain up to 20–30% lignin–hemicellulose–have potential biotechnological values because of their bioconversion and/or fermentation to yield industrially important constituents including biofuels (Sorek et al. 2014). However, due to the recalcitrant nature of the lignin, which has resistance against microbial attack (Loow et al. 2017a), cost-efficient methods to reutilize the lignocellulose components within the biomass effectively have remained challenging (Loow et al. 2017b). Much of the lignocellulose wastes create environmental pollution problems if remained in the farm either as biomass or burnt upon. Huge amount of lignocellulosic wastes if converted to the value-added products using enzymes such as cellulases, glucanases, hemicellulases, glycosidase hydrolases, polysaccharide lyases and carbohydrate esterases or with the help of microbes (Himmel et al. 2010) can yield chemicals, fuel, textile, paper, and agricultural inputs (Pothiraj et al. 2006).

Bioconversion, more specifically composting of agricultural residues refers to step-wise biodecomposition procedures carried out due to the intervention of different microbial communities under aerobic conditions (Pan et al. 2012). The end product of the aerobic composting yields stabilized organic product, which is beneficial for plant growth and development. Efforts on microbial intervention for better decomposition gained strength from the identification and characterization of such microbial communities from the agricultural soils, composts, vermicompost and humus-rich sites, that prominently catalyzed biodegradation and decomposition (Eida et al. 2012). Scaling-up of bioconversion processes and large-scale production technologies using microbial inoculants have resulted in producing mass-scale composted material that may be bioaugmented with beneficial microorganisms or fortified with organic inputs, bioinoculants, and vermicompost (Singh and Sharma 2002; Nair and Okamitsu 2012; Malusá et al. 2012). Composted products were reported to act as soil conditioners in low-cost crop production practices for resource-poor farming communities (Gajalakshmi and Abbasi 2008).

The uniqueness of microorganisms and their functions have made them potential candidates for decomposing agricultural residues into valuable products (Kumar and Sai Gopal 2015). Microbial communities have emerged to influence litter decomposability and size of nutrient pool in the soils. They primarily immobilize mineralized nutrients into microbial biomass and release nutrients from microbial pool after decomposition (Sahu et al. 2018). This phenomenon has major impact on the bioavailability of nutrients to the plants (Miki et al. 2010). It further regulates cycling of nutrients into the soils. Various microorganisms possess enzyme activities directly linked to the decomposition of organic materials which under improved composting conditions yield better compost products (Eida et al. 2012). There have been several reports on the isolation and trait characterization of microbial communities that can perform functionally better in combination with the existing rhizosphere bacteria, beneficial mycorrhizal fungi and biological control agents (Boulter et al. 2002; Anastasi et al. 2005; Vishan et al. 2017). The decomposed organic matter when used in the soils makes native beneficial microorganisms more effective due to their rich carbon content (Meena et al. 2014; Rashid et al. 2016). Vermicompost, a composted product produced by the intervention of earthworm *Eisenia fetida* is also known to enhance native soil microbial diversity and promote plant growth (Lim et al. 2015). Bacterial diversity from vermicompost exhibiting plant growth promoting traits has been investigated (Singh and Sharma 2002; Pathma and Sakthivel 2012). Co-inoculation of beneficial bacterial and fungal organisms like species of *Rhizobium*, *Azotobacter*, *Azospirillum*, *Pseudomonas*, *Bacillus*, *Burkholderia cepacia*, *Candida oleophila*, *Coniothyrium minitans*, *C. sclerotiorum*, *Aspergillus niger*, *Fusarium oxysporum* (non-pathogenic), *Gliocladium* spp., *Phlebia gigantean*, *Pythium* *oligandrum*, *Streptomyces griseoviridis* and *Trichoderma* spp. with organic matter-rich compost can add to the soil health. Such practices are known to improve crop productivity through diverse mechanisms through nutrient acquisition, mineralization, carbon addition and phytohormone production (Rashid et al. 2016; Meena et al. 2017). The species of *Rhizobium*, *Azotobacter*, *Azospirillum*, and phosphate solubilizing microorganisms that are currently being used as commercial formulations of biofertilizers, when added in combination with the compost can also provide major support to agriculture (Reddy and Saravanan 2013; Sharma et al. 2013). Use of farm yard manure (FYM), vermicompost and other humus-based organic farm inputs also support agricultural production. Overall, organic and microbially fortified farm-supplement constituents as termed by the names biofertilizers, biopesticides, microbial inoculants, soil conditioners if used in an integrated manner can make soils more live, healthy, and viable for improved crop production (Parnell et al. 2016).

Microbial bioconversion of agricultural waste, household waste or other natural products like leaf litter and non-decomposed matter into compost products was developed in the past several years. Various microorganisms were reported as fast decomposers, biodegraders, and bioconverters of non-useful products (Gautam et al. 2012). Fungal communities develop fast in the arable soils in straw residue degradation conditions (Ma et al. 2013). Rapid changes have also been observed in primary decomposer fungal communities suggesting that litter decomposition is a highly complex process mediated by diverse taxa (Voříšková and Baldrian 2013). Bacterial succession on plant residual biomass decomposition also exhibits specific pattern of bacteria and fungus communities. Results on bacterial succession suggested early-stage (2–4 months), mid-stage (6–8 months) and later-stage (10–24 months) prominent changes in decomposer communities (Tláskal et al. 2016).

The role of microorganisms as bioconversion agents is important due to their fast ability to convert cellulosic and lignocellulosic wastes into organic materials (de Souza 2013). Mature compost in combination with microbial consortia more prominently helps bioremediation of environmental pollutants (petroleum hydrocarbons) (Gomez and Sartaj 2014). It also improves microbial interaction with root rhizosphere to promote plant growth and develop top-soil structure (Sinha et al. 2009; Abhilash et al. 2016; Marcela et al. 2017). Composting process usually involves three phases in which diverse microbial organisms like bacteria, actinomycetes and fungi act on the lignocellulosic components of the residue biomass. This converts waste into humus under mesophilic (*Streptomyces rectus*) and thermophilic (*Actinobifida chromogena*, *Thermomonospora fusca*, *Microbispora bispora*) conditions (Pan et al. 2012; Zeng et al. 2016). The first phase initiates with the rise in temperature and reduces substrate by degradation action of mesophiles (Zeng et al. 2016). This is followed by the increase in the temperature up to 70 °C due to the abundant activities of thermophilic microorganisms (Schloss et al. 2003). Benefits of the thermophilic phase lie in terms of the loss of pathogenic bacteria and fungi which are degraded due to high temperature. Afterwards, the compost pile temperature returns to normal stage (Novinscak et al. 2008). The process of decomposition of crop residues involves differentially variable conditions (pH, temperature, moisture, nutrient availability) for the microbial communities involved during the period of degradation. Certain organisms like *Coprinus* species belonging to Basidiomycota grow well in alkaline conditions while other fungi, e.g., *Trichoderma*, *Mucor*, *Nocardia*, and *Phanerochaete chrysosporium* need optimum pH (5.5–8.0) for attaining high population that could help rapid biodegradation (Varma et al. 2017). The decomposition ability of the microbial communities is largely influenced by the conditions of the residual waste products being decomposed like pH (< 7.0), moisture content (~ 60%), volatile ammonia emission (30–70%), temperature (30–60 °C) and different organic mixtures (polysaccharides, cellulose, hemicellulose, amino acids, and fatty acids) (Urbanová et al. 2015). Conventional processes were reported in the past but rapid composting using microbial consortia is more advanced and advantageous concept due to the ease of controlled environment, identified ingredients for fast degradation and timely composting (Chen et al. 2016; Patchaye et al. 2018).

The enteric fermentation of the ruminants from the livestock, especially of the cattle used at large scale in agricultural practices leads to the production of green house gases (GHGs). One such gas methane (CH_4) contributes to almost 1/3rd of the total emissions of GHGs from agricultural sector (https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#agriculture). The other gaseous emission in agricultural sector that largely contributes to GHGs in the environment includes nitrous oxide and carbon dioxide, the mitigation of which needs specific technologies associated to irrigation type and nitrogen use status (Sanz-Cobena et al. 2017). Improper manure management, burning crop residues in the fields, application of synthetic nitrogenous fertilizers and high nitrogen crops are the major factors that contribute to the GHGs in the environment (http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=115). Agricultural residues or animal wastes, when left in the fields for months have possibilities of uncontrolled decomposition by undesirable bacteria or fungi and therefore, are liable to produce more amount of GHGs (Patra and Babu 2017). Associated with this, there always remains risk of polluting air and water with nitrogen and microbial pathogens (Venglovsky et al. 2009). For this reason, safety concerns for the use of animal manures in the soils by spreading onto the land is challenging and needs various treatment methods for the deactivation of pathogenic microbial species (Martens and Böhm 2009). However, the controlled composting such as conversion of pig slurry into pellets help farmers improve soil properties due to reduction in ammonia volatilization and mitigate GHG emissions (Pampuro et al. 2017a, b). Microbe-mediated controlled composting yields composted products from livestock wastes also in a time-lined manner with the use of known microbial degraders and specific ingredients. This becomes helpful in obtaining decomposed products of specific C:N ratio having beneficial microbial communities for direct field utilization (Ng et al. 2016).

Technological aspects of microbial bioconversion of agricultural wastes

One of the major identified reasons for declining agriculture sustainability is poor soil condition due to reduced application of organic matter into the farms and non-conservational practices that majorly disturb top soils (Kibblewhite et al. 2008; Hobbs et al. 2008). Huge volume of agricultural wastes in farmer's fields has economic and environmental benefits as suggested by the studies on pyrolysis and biochar of rice straw, corn stover, orchard, and animal wastes (Kung et al. 2015). Crop wastes blended with the cow dung for biogas production after anaerobic digestion using anaerobic bacteria (acidogenic and acetogenic bacteria) generate electricity through potential technologies (Muthu et al. 2017). The product of anaerobic digestion after waste treatment or the digestate remains can add value through decomposition. Prominent microbial community dynamics was observed when the anaerobic digestate from the municipal food residues, and green and kitchen wastes were composted under natural composting conditions (Franke-Whittle et al. 2014). Understanding on microbial dynamics during different phases of composting helped better control of bio-oxidative processes followed by stabilization and maturation phases that use specific technology in static reactor of high capacity (up to 600 L or more) (Villar et al. 2016). Studies have opened new avenues for better utilization of anaerobic digestate after improved composting using beneficial microorganisms, the products of which could be directly utilized in the farms for improving soil organic content (Zeng et al. 2016). Such composts proved to be good alternatives of farmyard manures for field application.

Composting technologies are farmer-friendly, reproducible, easy to adopt and yield productive inputs for the farms to sustain agricultural productivity beside generating biogas for bioenergy (Achinas et al. 2017). Agricultural residues have remained tremendous sources of bioenergy worldwide. Crop dry matter and oil-rich residual biomass have attained the attention due to their huge yearly quantitative volume of ~ 11.33 million tons that could be converted to 3.84 giga-liters (GI) of bioethanol, 1.07 GI biobutanol, 3.15 billion Cu-Meter (BCM) biogas and ~ 1.0 BCM of biohydrogen (Karimi and Yaghmaei 2016). Under methanogenic condition, hydrogen, carbon dioxide, and methane are generated due to the action of degrading enzymes on residual crop biomass. Another important aspect of crop residual resource management lies with the characterization and thermal conditioning of bio-oils into fuel production (Bertero et al. 2012). These technologies, based on the microbial role in waste bioconversion have also been developed for the production of ethanol, biofuels, platform chemicals, and biorefinary products (Mielenz 2001; Prassad et al. 2007; Weber et al. 2010; Msangi 2012). In India, nearly 700 million tons of organic residual wastes are generated annually (Nagavallemma et al. 2004). One of the most prominent ways of the safe disposal of the majority of waste is composting which is an environmentally sound bioprocess of converting organic residual wastes into valuable products for farms (Pan et al. 2012). Besides, if scaled up and industrialized, these products can also meet alternative fuel needs through sustainable waste management practices (Weiland et al. 2009). Various microorganisms, their potential constituents that help in fast decomposition, biodegradation and bioconversion of crop residues and other valuable products are listed in Table 1.

Microorganisms are the major key players in maintaining nutrient flow from residues to the farm soils (Erickson et al. 2009). Plant materials, especially the crop residues are rich in lignocellulosic biomass but have crystalline structures embedded with silica, lignin, suberin, and other polymeric constituents that hinder the process of smooth microbial degradation for composting (Huber and Praznik 2004). Therefore, pretreatment of lignocellulosic biomass with the help of acid, alkali, steam, urea, and hydrolytic enzymes is recommended for substantial breakdown of hard constituents to smoothen the process of composting (Mosier et al. 2005; Table 1). Lignolytic enzymes produced by some potential microbial isolates can also be a source of rapid biodegradation module for large-scale and effective lignin degradation (Table 1) (Fenga et al. 2011). The role of gut microorganisms like *Coptotermes formosanus* isolated from termites is also important in changing physicochemical properties of the crop residues. Cellulose and lignins can be made readily available for the existing microbial communities for degradation (Harazano et al. 2003). Potential microorganisms with impressive enzymatic capabilities for fast degradation of recalcitrant lignin are discussed (Table 1) (Perez et al. 2014; Varma et al. 2017). Since these organic compounds possess complex interlinked fractions, their biomass valorization is tough and highly resistant to hydrolysis and solubilization (Kumar and Sharma 2017). Therefore, instead of a single process for pretreatment, multiple physical, chemical, and biological steps are required in an integrated way to minimize undesirable inhibitors (Masran

Table 1 Various bacteria and fungi have been isolated, identified, and their products, especially enzymes were used for enhanced decomposition and degradation of agricultural residues into compost

S. no.	Microorganisms	Biodegradation activity	Nature of organic matter	References
Fungi				
1.	*Pleurotus sajor-caju*	Exocellular lignocellulose degradation	Multiple matters	Singh (2000)
2.	*Pleurotus flabellatus*	Exocellular lignocellulose degradation	Rice straw, sisal leaves	Mshandete and Cuff (2008)
3.	*Pleurotus eryngii*	Lignocellulose degradation, laccase enzyme activity (degradation of phenolics)	Agricultural wastes	Yildirim et al. (2015)
4.	*Aspergillus niger*	Cellulase, xyalanase production	Pre-decomposition of organic matter, sugarcane bagasse	Singh and Sharma (2002); Romero et al. (2007)
5.	*Trichoderma harzianum*	Hemicellulose degradation (hemicellulase production)	Pre-decomposition of organic matter	Singh and Sharma (2002); Jorgensen et al. (2003)
6.	*Trichoderma reesei*	Cellulase and hemicellulase production	Commercial production of enzyme for degradation	Nieves et al. (1998)
7.	*Penicillium brasilianum*	Cellulases and xylanases production	Commercial production of enzyme for degradation	Jorgensen et al. (2003)
8.	*Phanerochaete chrysosporium*	Lignin peroxydases, glyoxal oxidase, manganese peroxydases (lignin degradation enzymes)	Lignin-containing biomass like wood shavings, agro wastes	Martinez (2002), Kersten and Cullen (2007) and Zhang et al. (2013)
9.	*Xylaria hypoxylon*	Xylanase, laccase, glucosidase, esterase	Woody materials	Liers et al. (2006)
10.	*Pycnoporus cinnabarinus*	Lignin peroxidases, manganese peroxidases, laccase	Woody materials	Alves et al. (2004)
11.	*Trametes versicolor*	Laccase	Agro wastes and woody substrates	Cabuk et al. (2006)
12.	*Aspergillus awamori*	Cellulases	Agro wastes	Gaind and Nain (2007) and Pleissner et al. (2013)
13.	Paecilomyces marquandii	Keratinase	Poultry waste (feather waste)	Veselá and Friedrich (2009)
14.	Phanerochaete chrysosporium	Increases the humification degree of humic acid	Agro waste	Huang et al. (2009)
Bacteria and actinomycetes				
15.	*Bacillus* sp.	Lignin degradation	Degradation of pulp paper waste	Chandra et al. (2007)
16.	*Paenibacillus* sp.	Lignin degradation	Degradation of pulp paper waste	Chandra et al. (2007)
17.	*Aneurinibacillus aneurinilyticus*	Lignin degradation	Degradation of pulp paper waste	Raj et al. (2007)
18.	*Pseudomonas putida*	Manganese peroxydases and laccase	Agro waste	Ahmad et al. (2010)
19.	*Pseudomonas aeruginosa*	Manganese peroxidases, lipid peroxidase and laccase	Agro waste	Bholay et al. (2012)
20.	*Serratia marcescens*	Manganese peroxidases, lipid peroxidase and laccase	Agro waste	Chandra et al. (2012)
21.	*Citrobacter freundii*	Manganese peroxidases, lignin degradation	Agro waste, saw dust	Ali et al. (2017)
22.	*Streptomyces* spp.	Cellulases, xylosidase, acetylesterase, xylanases	Agro waste	Benimelia et al. (2007)
23.	*Bacillus licheniformis* and a Streptomyces sp.	Keratin degradation by Keratinases	Poultry waste	Ichida et al. (2001)
24.	Mono and co-cultures of *B. subtilis* and *P. ostreatus*	Cellulase	Apple and plum wastes mixed with cereal wastes.	Petre et al. (2014)
25.	Geobacillus strains	Boost the total bacterial count	Vegetable waste	Pal et al. (2010)
26.	*Stenotrophomonas maltophilia*, *Scedosporium apiospermium*	Biodegradation of asphaltens	Asphaltens from Prestige oil spill	Martín-Gil et al. (2008)
27.	*Bacillus cereus*, *Bacillus megaterium*	Breakdown of cellulose and hemicelluloses	Organic substrate	Ribeiro et al. (2017)

et al. 2016; Shrestha et al. 2017). Maintenance of proper pH, temperature, air (oxygen) and moisture conditions and softening of the surface layer of residual biomass with the help of surfactant or urea is helpful. Likewise, fungal treatments in which fungi and actinomycetes directly colonize with the residues or enzymatic treatments using lignolytic enzymes help improving biodelignification process (Ilyin et al. 2004; Moreno et al. 2015). It further needs exposure of suitable mesophilic and thermophilic conditions that may include combined organic and inorganic complexes like $CuSO_4$-gallic acid supplement for aggravating high functional bioconversion activities (Mishra and Jana 2017).

The bioconversion process can be fastened with the use of such functionally characterized microbial inoculants that possess high enzymatic activities for lignocellulosic degradation (Choudhary et al. 2016). Industrial composting for mushroom production is an established biological procedure to produce *Agaricus bisporus* (Jurak et al. 2014). Mushrooms are among the most fascinating fungal organisms to be used as pretreatment degraders of the lignocellulose constituents of crop residues and perform improved enzymatic release of monosaccharides for biofuels. It also helps to convert residual biomass into valuable protein-rich edible fruits of high nutritional importance (Jurak et al. 2015). Compost preparation for mushroom production involves microorganisms that decompose natural lignocellulose into simple mineral components, on which mushroom mycelial mass grows and produces fruiting bodies (Mouthier et al. 2017). Therefore, besides obtaining high-value protein-rich functional food product from the bioconversion of crop residues by mushroom fungi (Chang 2008), farmers can also get value-added compost for their farms to enhance crop production and soil fertility. Fortification of raw compost with plant growth-promoting bacteria and biocontrol agents like *Trichoderma harzianum* potentially enhance suppressiveness of soil-borne diseases and efficacy of compost microbiota against pathogenic diseases (Pugliese et al. 2011; Ros et al. 2017). Mushroom production is of high economic significance in many parts of the world (Marshall and Nair 2009; Zhang et al. 2014) and compost fortified with beneficial microorganisms also has potentials of enterprising (Awad and Khaled 2012; Sarkar and Chourasia 2017).

Direct composting of agricultural crop residues using large windrows allows thermophilic conditions to convert high volume of lignocellulosic wastes into stable compost with specific ingredients of definite C:N ratio (Vigneswaran et al. 2016). The whole process is biochemically sound and mediated by microbial metabolic activities that produce heat, water, CO_2 and results in mineralization, transformation, and humification (Shilev et al. 2007). The technology is cheaper and sustainable in terms of its requirements for ingredients, manpower, energy, water, time, resource integration, and reproducibility. As far as the agricultural benefits are concerned, in controlled and defined conditions, the process can yield organic matter disinfected by high temperature. It is also a mineral-rich nutritional substance that improves structural components of the soil by degrading large complex molecules into simple ones for soil fertility (Sonesson et al. 2000). After production of good-quality compost using windrows, biofortification of the raw product can be done with the use of beneficial microbial inoculants (plant growth-promoting bacteria, mycorrhiza, and biocontrol fungi) (Muttalib et al. 2016). Enrichment of raw compost material with organic inputs like humic acid, amino acids, phytohormones, mineral nutrients (zinc, iron, boron), phytonutrients, botanicals and vermicompost can further add value to the products that can help in organic farming (Mohler and Johnson 2009).

Large-scale livestock production systems are the source of huge amount of agricultural residual biomass of manures and slurries that can be applied to the land for fertility improvement (Bernal et al. 2009). Pig slurries and poultry manures have remained a common source of composting ingredient (Pampuro et al. 2016). Co-composting of wastes from winery distilleries with animal and poultry manure under static pile composting system was assessed on different parameters such as pH, electrical conductivity (EC), organic matter, soluble carbon, polyphenolics content, humification characteristics, and plant germination index (Bustamante et al. 2008). Agricultural food wastes are also attractive composting materials for their conversion into decomposed manures to be used for producing high-value crops (Rubio et al. 2013). It was largely considered that composting processes that ensure nutrient-rich conditions, appropriate carbon rating, organic matter humification and adequate bulking for reducing N-losses are required to overcome production cost (Bernal et al. 2009). Results confirm that composting helped in detoxification and degradation of phytotoxic compounds in the residual matter and therefore, offers a favorable way to recycle wastes into value-added products (Pampuro et al. 2016).

Potential benefits of microbe-mediated compost as farm inputs

The role of microorganisms as bioconversion agents and their ability to convert cellulosic and lignocellulosic wastes into organic materials, bioremediate environmental pollutants and interact with root rhizosphere to promote plant growth and soil structure were defined (Sánchez 2009; Huang et al. 2010). They are inevitable for the natural resource management in the farmers' fields. Controlled composting guided by microbial interventions dependent on defined microbiological processes to decompose agricultural residues properly and timely and produce high-value low-cost bioorganic farm inputs (Ahmad et al. 2007; Singh and Nain 2015; Singh and Prabha 2017; Sudharmaidevi et al. 2017). This is how rapid composting processes can help farmers in timely production of compost and fortified bioorganic farm inputs of desired quality for organic farming needs and high-value commercial crops like vegetables, fruits, flowers, and organic crops (Hoornweg et al. 2000; Seyedbagheri 2010). If farmers need biopesticide-rich compost material for the control of soil-, seed- or seedling-borne fungal pathogens in the field, they can biofortify the raw compost with bioagents (Siddiqui et al. 2008; Ng et al. 2016). Similarly, consortium of microorganisms fixing nitrogen, solubilizing phosphorus and zinc and mobilizing potassium can be utilized to fortify raw compost material for desired quality under suitable enriching conditions of temperature and moisture. This can yield potential bioorganic inputs enriched with N, P, K and Zn-harvesting and recycling microbial population (Pugliese et al. 2011; Baig et al. 2012; Kamran et al. 2017; Pallavi et al. 2017). The whole process remains at the ease of the farmer's need, expertise, indigenous resource availability, local conditions, and existing human resources.

Microbe-mediated activities that favor efficient composting processes, technological aspects of agrowaste bioconversion, microorganisms involved, benefits of microbial fortified and enriched compost and options for adopting such microbial technologies as models of eco-enterprising are discussed. All these steps are simple and easily adaptable by the farming communities. Also, the ingredient resources are usually available with the farmers at their homes. The method is helpful in reintroducing organic matter to the soils along with the beneficial microorganisms that help soils to improve nutrient status for plant growth and development. Adoption of such practices in farmers can not only increase rural sanitation at ground level and support cleanliness drives of the governments worldwide, but can improve soil fertility status also. The method yields value-added low-cost farm inputs from the agricultural farm residues that would otherwise go waste. When burnt at farmer's fields, it creates obnoxious green house gases (GHGs), fog, and smog. These products are enriched with microbial consortia of plant growth promoting and biological control microorganisms. These organically rich bio-farm inputs have functional benefits of microorganisms.

Agrowaste bioconversion as eco-enterprising model

Proper utilization of agricultural crop residues can benefit farms and farming communities. When developed in the form of an eco-enterprising model, microbe-based bioconversion of crop residues can be of immense help of rural communities to generate rural livelihood through the products of commercial utility (Naresh 2013). Mushroom production in rural parts of many countries has gained the shape of eco-business because of prominent reasons. Firstly, it has rooted in locally available farm residual resources, which usually go waste. Secondly, it can be performed with practical skills, which may be inculcated in the farming communities through learn-by-doing methods and thirdly, it can yield high-value food for family use and/or additional income, if commercialized (Marshall and Nair 2009; Valverde et al. 2015). Looking into the potential benefits of mushroom production in terms of high-value food, waste utilization and spent management (as enzymes, proteins or microbe-fortified compost) (Phan and Sabaratnam 2012; Kumar et al. 2014), prospective eco-enterprising model for rural farming communities or agro-industries can be developed (Celik and Peker 2009). A workable and integrated eco-enterprising model of agrowaste bioconversion and fortification with the help of beneficial microorganisms is presented (Fig. 1). The model can be promoted into the farming communities to attract resource-poor farmers towards various biological, technological and commercial aspects of on-farm bioconversion agro-waste management. This may also be helpful in strengthening the rural economy at a developmental stage by introducing diversified business and income generation opportunities for the rural people (Singh et al. 2010).

It has been demonstrated that the bioconversion of crop residues like straw, husk, corn cobs, bagasse and vegetative materials coming from regularly grown field crops can be converted into raw compost using windrows at farmer's fields (Singh and Prabha 2017). The raw compost was further fortified with the plant growth promoting microorganisms or biocontrol agents like *Trichoderma* and *Pseudomonas* to scale up the efficiency of microbial formulations (Galitskaya et al. 2016). The strength of raw compost can also be improved by the addition of poultry wastes and degradation with the help of microbial enzymes (Brandelli et al. 2015). In the very simple steps, bioconversion processes of agricultural wastes can be disseminated among rural population for adoption of such microbe-based models of biobusiness. The impact of pelletizing pressure for developing solid state compost from different composting materials like pig solid fraction, bulking agents, e.g., biochar and wood chips, swine manure solid fractions and organic co-formulates was assessed for standardizing physical and mechanical properties of the composted material (Romano et al. 2014; Pampuro et al. 2017a, b). These studies resulted in developing farmer-friendly and easily adaptable composted products with quality standards for commercialization and enterprising. These models are supposed to be developed for introducing multi-enterprising support for smart agriculture system (Pramanik et al. 2013).

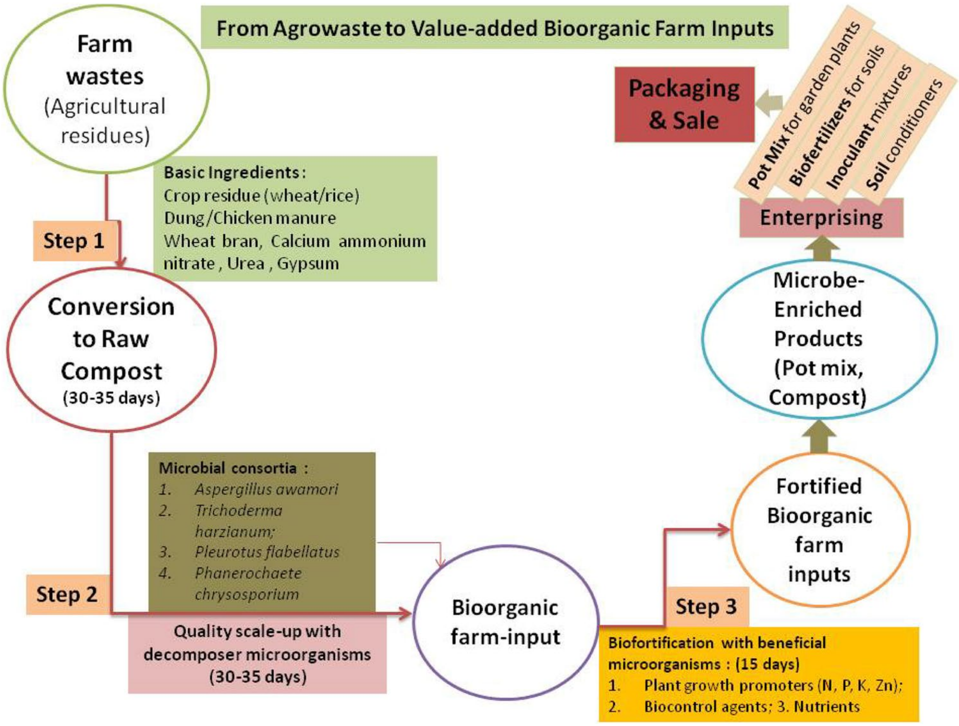

Fig. 1 Agrowaste bioconversion model based on crop residues as primary composting resource in three steps (1) agricultural waste (wheat, paddy straw, and crop leaves) is converted into raw compost in 30–35 days using different kinds of ingredients (C:N ratio 17:1); (2) raw compost is further decomposed in next 30 days using decomposer microbial consortia to produce bioorganic farm inputs with C:N ratio of 30:1 and (3) fortification with beneficial microorganisms like nitrogen fixers, phosphate solubilizers, biocontrol agent(s), humic acid, micronutrients for 15 days to obtain microbe-enriched products for direct farm applications

High input-based farming systems, in which chemical inputs play a major role, are becoming problematic owing to the loss of diversity of native phyto-, micro- and zoo-biota and non-responsiveness of the soils (Shennan 2008). Excessive chemical usage has also led to serious imbalances in natural ecosystem of the soils and created threat to the fertility, structure and function of soils, crop intoxication, productivity losses and damaged harmony of crop–soil interactions (Aktar et al. 2009). Therefore, a farming system that promotes better utilization of farm residual resources and usage of low external inputs is the need of the time. Such a system will engage locally available sources with the farmers and make better use of their own field resources to obtain better results while minimizing dependency on high external costs on inputs. This is why, microbial technological interventions essentially need to be propagated into the farming communities to obtain better functional food, enhance soil organic matter by applying self-produced low-cost composts and microbiologically enriched farm inputs for strengthening field soils.

Linking farmers with agrowaste bioconversion

Adoption and adaptation of farmer-friendly microbe-mediated agrowaste bioconversion technology for composting among the grass-root stakeholders is a matter of perception and preference. Less awareness on soil and plant characters, lack of perception for linking up agricultural foods with human health, low tendency to adopt new technologies, short-sightedness towards long-term benefits and weak chain of awareness managers are the key factors that restrict direct penetration of valuable technologies among farmers. Awareness on these technologies and penetration into the farming communities either through ICT tools or by videos, learning materials or by technical demonstration kits may enhance technological adaptation (Karubanga et al. 2017). Some case studies on adaptation of pelletized compost from animal manure in the farming groups in Italy (Pampuro et al. 2018) and promotion of bioconversion technology in Indian farmers demanded targeted information campaigns, trainings, live product demonstrations and on-farm production applications to generate hands-on-experience. These efforts can yield desirable impacts on promotion of integrated farm management practices and soil fertility level to bring back countable changes among farming communities (Muller 2009). The outcome can be witnessed in terms of reducing dependency on high-cost chemical fertilizers, minimizing risk of pollutants due to residual effects of pesticides, lowering production cost of the crops, enhancing yield quality of production of commercial crops, ensuring increased fertility of farm soils and generating income after sale of the compost products (Aktar et al. 2009; Settle et al. 2012; Yadav et al. 2013). The concerns of direct farmer's benefits in reducing the input cost for crop production, improving soil and plant quality, creating wealth from waste through eco-enterprising of composted products and applying microbe-rich compost in organic farming practices are important. Therefore, the Indian government has shown keen interest in promoting adaptation of such environment- and agriculture-friendly practices in farmers through various developmental schemes and funding projects (https://nmsa.dac.gov.in/; http://midh.gov.in/; http://agricoop.nic.in/sites/default/files/OPG1922016.pdf).

Conclusion

A reductionist approach towards the use of chemical fertilizers and pesticides is the need of the day across the world. Minimizing farm chemicals can solve various problems of the present-day agriculture, especially those which are directly linked with the soils, plants and human health and raise negative ecological impacts. Available post harvest crop residues create sanitation problems in the rural areas due to uncontrolled anaerobic degradation. While using excessive chemical fertilizers, farmers have almost forgotten to add organic carbon to the soils and this has resulted in lowering the carbon content of the soils over a time scale. Low organic carbon content soils usually become non-responsive to support life of microorganisms, microflora, and fauna and thus lose biological functions. Live soil systems are the integrated part of the crop ecosystem to perform major ecological functions, which majorly include nutrient recycling, carbon sequestration, mineralization, availability of organic substances and volatiles. If crop residues are burnt in the farms, they disturb microbiota of the productive top-soil layers on one hand and pollute air quality on the other. With the help of microbial interventions and developing skills among the rural population, the raw residues can be transformed firstly into mushrooms of high nutrition value for nourishing food and subsequently, the spent waste can further be biologically converted into microbe-enriched compost having specific functional trait. The second option for the on-farm utilization of the crop residue is the need-base production of raw compost from the available residual resources. Its further bioconversion and fortification into bioorganic farm inputs with the help of potential microorganisms with multifunction can be of immense importance for the farming communities. One of the major benefits of using bioconversion technology for agrowaste bioconversion is to making feasible the availability of ready-to-use organic input in the soils. Secondly, this can also help to add desired microbial communities with specific functions, which, if added without any support of organic matter, may not flourish in the low-carbon soils. Thirdly, proper availability of bioorganic materials in the soil supports and enhances nutrient use efficiency of the soils and ensures proper availability of micronutrients for longer time durations. Apart from these direct benefits, there are furthermore benefits associated with application of compost and biofortified farm inputs. Presence of beneficial microbial communities in the soils makes their interactions feasible with the roots of the plants and thus, strengthens rhizosphere. This will help in the plant immunization and making crops resistant against pests and diseases and tolerance against abiotic stresses. In an integrated way, these microbe-mediated processes help improve ecological services around the plant roots and support soil fertility.

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